Boston University Institute for Sustainable Energy

Water Planning in an Age of Change

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This review paper examines a variety of methodologies that underpin current water planning in the United States – spanning the city, state, and Federal scales – and identifies ways in which changing realities and greater interdependencies between various different critical infrastructures are driving the need for new water planning approaches and processes. Specifically, new sources of uncertainty and their implications are examined, and challenges relating to water supply, allocation, decision making, safety and security, and the information and processes of planning are delineated.

In this context, the usefulness of adding scenario planning to current water planning processes is assessed, and ways in which it can be implemented effectively are described. Opportunities for One Water planning to be augmented by critical infrastructure planning and enhanced risk mitigation are also discussed. Recommendations are articulated that are relevant to states, cities, and utility agencies, in order to ensure that they are more resiliently prepared for a substantially more uncertain planning environment in the future, with particular attention to critical infrastructure for water and for other services and the interrelationships between them.

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All results and any errors in this report are the responsibility of the author.

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Summary

The State of Water Planning in the US

Water planning in the US is a well-established institutional process with generally consistent structure and methodologies. It provides clear documentation of the state of water supply and demand, infrastructure integrity and challenges, and forthcoming capital projects and service adjustments needed to maintain both water quality and quality of service to utility customers.

Water planning co-evolves with the policy landscape in which it occurs. Presently, water planning is gradually shifting its focus to sustainability principles and priorities, e.g., ecosystem conservation, restoration, and water reuse.

Certainly, policy shifts at the Federal, state, and local level influence planning processes and practices. Disruptive impacts stemming from ecological challenges influence local and state level changes in forward planning. Sources of disruption range from local impacts of pollution to global climate impacts, such as rising sea level effects on water and wastewater systems.

These disruptions include impacts of interdependencies amongst a diverse mix of critical infrastructures, which are essential to ensuring a thriving advanced economy. The links between electric power and water are especially important. However, of near-equal importance are interdependencies amongst communications, information technology, and transportation.

Address Uncertainty

Increased attention is needed regarding unanticipated, significant qualitative changes that disrupt contemporary planning processes. Paramount examples in recent years include cases where whole cities find themselves on the brink of literally running out of water. The most notable case, perhaps, is Cape Town, Republic of South Africa, but Australia and some vulnerable US cities, such as Los Angeles, Las Vegas, and Phoenix, are also increasingly at-risk water supply cases.

The root of most critical issues in water supply chains is the shifting availability of water resources in quantities needed. Also, prudent use of water by consumers always has been a concern, but its importance is rising as supply challenges amplify. Pricing strategies, conservation practices, innovative water reuse, and many other technology and practice changes are being implemented more broadly.

One outstanding change in water planning facing Federal, state, and local entities is a shift in the scope and methods of dealing with uncertainties and more evident interdependencies. Water sourcing, delivery, quality assurance, and financing are challenged as supply availability stresses other contemporary systems, such as electricity production and distribution.

A water planning methodology designed to better contextualize uncertainty and prepare for less predictable outcomes is an important enhancement to well-managed present practices. Robust quantitative models used for water supply planning are less effective than judgement from experienced subject matter experts at the frontiers of unprecedented events. New uncertainties, like climate change impacts, often take time to curate for effective quantification and integration into planning models. Qualitative tools are useful for mapping unprecedented circumstances; they provide a bridge that facilitates the integration of unprecedented event typologies into contemporary planning models.

Scenarios offer the best tools for capturing the qualitative aspects of uncertainty. They can paint pictures of possible outcomes stemming from the convergence of ecological, social, and technological forces. When effectively applied, scenarios enhance decision-making and help prioritize which factors or variables within an uncertainty matrix are most important. For example, is equitable water allocation more important than strategic allocation (which may be inequitable) for essential purposes such as agriculture during a protracted drought?

An emerging dimension of uncertainty and surprise merits uptake and integration into contemporary planning processes. Water, like electricity, energy, communications, and transportation is an essential service, i.e., a "critical infrastructure" (CI). There are interdependencies amongst CIs that can complicate and augment problem definition and architecting solutions if they are under appreciated. Scenario planning is especially helpful in articulating risks and implications at the interface of multiple critical infrastructures. Enhancing water planning means integrating CI cross impacts. This can be done at low cost and high impact value when scenario planning is properly applied.

Use Scenarios as a Key Element in Water Planning

Scenarios are intended to bracket the extreme possibilities against the effects of continuing with status quo or with slow incremental change pathways. Scenario planning methodology, pioneered by Royal Dutch Shell in the 1970s, still is used in the energy space and has been adopted by the United Nations Economic Commission on Europe (UNECE) as a tool for analyzing the UN's sustainable development goals for 2030. These goals include the provision of clean water and affordable and sustainable energy. The aim of the UN's use of scenario planning is to improve the understanding of various policy pathways that can help or hinder efforts to mitigate climate change.

Scenario planning as an add-on to existing water planning serves the same aims as the UN and the UNECE. It can help articulate complex issues that are yet to be thoroughly quantified for decision-makers. Understanding cross impacts of critical infrastructure interdependencies also is achieved quickly and thoroughly when scenario planning techniques are applied. Specifically, the "water-energy-food nexus" is becoming an essential planning and policy domain, which promises to reshape energy, water, and food related planning at various jurisdictional levels in the coming decades.

Add Critical Infrastructure Planning and Risk Mitigation to One Water Planning

The present concept of One Water provides a clear framework for integrated water resource planning. It looks holistically at the planning and management of water supply, wastewater, and storm water systems. Further, the One Water framework focuses on the water cycle as a single connected system. It promotes coordinated development and management of water, land, and related resources to maximize economic and social benefits, while minimizing impacts on both natural and human ecosystems.

Water resources are impacted by decisions related to land use and growth management. Such decisions influence water demand, affect water supply, and impact water quality. The One Water model represents a platform shift in the management of water, both in terms of the physical systems that manage water and the institutional structures that prioritize various water management needs.

Finally, planners of all types across state and local jurisdictions are vital partners in facilitating One Water deployment priorities. Effective interdisciplinary collaboration between water managers, planners from multiple state and city departments (e.g., land-use, zoning, permitting, economic development and other functions), engineers, architects covering various aspects of the built environment, and public works managers are important to achieving optimal water management regimes with an eye on long-term sustainability of water supplies.

Converging interests are empowered to work collaboratively through One Water practices. However, interdependencies with other critical infrastructures may have more impact on water supply chains than contemporary water planning assumes. Disruptions from climate change and from opportunistic parties can interrupt electricity supplies, which impact water management and many other critical infrastructures. It is important to incorporate these increasingly significant impact factors into water planning, and to integrate water planning into higher level strategic critical infrastructure planning.

Recommendations

Water planning and CI planning merit more integration. This research finds that Federal critical infrastructure planning is focused on disaster anticipation and management. It leaves to state and local governments the operational challenges of mitigating risks stemming from interdependencies amongst multiple critical infrastructures.

ISE recommends that at the state level the following steps are taken to address the above:

1. Conduct a statewide review of existing CI plans and identify the extent of integration for dealing with interdependencies.
2. Based on findings in (1) develop a prototypical integrated CI planning process that leverages existing planning and minimizes added costs, while maximizing added benefits in each of the main CI sectors.
3. Following the work in (2), conduct a pilot program that adds scenario planning to contemporary infrastructure planning and uses scenario planning techniques to create planning tools that help to integrate CI sector plans into an overall, comprehensive state level CI plan.

Perhaps the most significant finding of this research is the scope of essential service interdependencies in the energy-water-food nexus. ISE recommends that this constellation of planning domains and how they overlap become the new framework for essential service and critical infrastructure planning for the state. On the basis of success here, states can extend contemporary CI planning relevance and ensure safe, reliable, and affordable essential services in an age of change.

What Follows

The issues noted above and implications for planning and policy-making are the subjects of this paper. In Section 1, multi-level water planning in the US is benchmarked. This sets the foundation for Section 2, which focuses on the changing water planning environment. Section 3 examines uncertainties and unprecedented risks which impact contemporary water planning processes and practices. Section 4 develops the use-value of scenario planning as a supplementary, or “add-on” tool, which can help enrich water planning in the context of critical infrastructure planning and vice-versa. Recommendations that states, cities, and utility agencies should take to be more resiliently prepared for a much more uncertain planning environment affecting critical infrastructure in particular ends the paper.

1. Multi-level Water Planning in the US

This section introduces the main tools that are used for water planning, outlines how scenario planning is presently used in water resource planning, and how it can be leveraged to enhance contemporary water planning methods and practices.

1.1 Unprecedented changes impact present water planning practices

Weather patterns drift year-to-year. Water supplies generally mirror weather patterns. Hot and dry years can mean water supply challenges, e.g., droughts and requirements to conserve. Cooler and wetter years enable water supplies to be replenished. The impacts of weather patterns vary according to population concentrations, land use patterns, and many other factors. Loss of water supply reliability can contribute to significant human migration patterns, which disrupt local areas, regions, and the national economy.

Critical infrastructure in the US has significant interdependencies between electricity, water, communications, and transportation. In today's world, separating these interdependencies risks overlooking critical cross impacts while yielding possibly more costly critical service delivery. It is why long-term water planning merits enhancements to address the implications of critical infrastructure interdependencies. That is, the scope of water planning is challenged to adapt to changes stemming from (but not limited to), (a) the digitalization of the US economy, (b) the increasing interdependencies amongst critical infrastructures as a consequence of (a), and (c) weather patterns exhibiting more pronounced drifts and attendant consequences from year to year. These issues are explored throughout this report.

1.2 Present water planning methodologies

1.2.1 Summary of main methods

Water supply planning uses a mix of quantitative modeling and analytical tools for assessing both near-term and long-term operating and capital requirements. Effective planning is needed to ensure reliable, safe, and affordable water service for US economies. There are seven principal methods used, each with specific limitations:

1. *Requirements based water planning[1], which focuses on identifying cost-effective technical performance factors that influence water supply and demand balancing.* Supply is determined by projected demand and costs of delivery are driven therefrom; causing misalignments between supply and demand balance that can yield inefficiencies in costs and infrastructure investments.

2. *Benefit-cost analysis[2], which focuses on maximizing net economic or financial benefits for owners, cities, regions, or nations, with alternatives suggested by stakeholders or from modeled*

[1] Daniel P. Loucks and Eelco van Beek, Water Resources Planning and Management: An Overview, Springer, 2017.

[2] Charles W. Howe, Benefit-Cost Analysis for Water System Planning, Volume 2, Wiley, 1971. Available at: https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/WM002

results. Explicit, technically derived, mapping of benefits and costs, often with explicit and unrecognized integration of potentially significantly impactful uncertainties.

3. *Multi-objective modeling*[3]*, which quantifies objectives set by decision-makers and stakeholders, maps alternatives suggested by Subject Matter Experts (SMEs) and reduces alternatives to the "Pareto-optimal" set.* Focus is on articulation of tradeoffs across and between objectives of major alternatives, requiring optimization using weighting factors influencing estimated value of alternative objectives; the problem for this modeling approach is that weighting factors can be subjective.

4. *Conflict resolution practices*[4] *using adaptive management principles where quantifiable objectives are specified by decision-makers and stakeholders, alternatives are framed by SMEs, and alternatives are shaped to long-term efforts to adapt, monitor, and narrow uncertainties.* Practices can use quantitative models to aid in solving problems, but conflicts can lead to abandonment of modeling for planning and decision-making.

5. *A variant of conflict resolution practices referenced as "watershed planning,"*[5] *which does not include formal evaluation techniques as part of the process.* This has the same issues as (4) above.

6. *Market-based water planning*[6]*, which involves competitive practices where objectives of parties are not necessarily revealed — options are identified by market participants and actions are taken consistent with individual objective functions.* Market participants act to achieve their own objectives independent of any collective considerations, resulting in outcomes that may skew benefits or leave value unrealized.

7. *Muddling through*[7]*, practices that reflect an incremental, principally reactive approach to planning with only simple and expedient alternatives considered.* Modest analysis is applied because the process itself reinforces minor adjustments against the "As Is" state.

1.2.2 Systems dynamics modeling for water supply planning

Systems dynamics (SD) modeling is designed from the ground up to integrate a complex mix of interacting variables. When applied to water supply planning, variables such as population patterns, diminishing water supplies, variable climatic conditions, and regional characteristics (such as aridity, "tropicality," or seasonality) can be integrated in both stochastic and nonlinear modalities. Systems dynamics based simulation analysis can help to shape workable water management strategies. These tools help planners cope with present and/or future water demand changes, as well as supply changes.

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[3] S.E. Schwetschenau, J.M. VanBriesen, and J.L. Cohon, "Integrated Multi-objective Optimization and Simulation Model Applied to Drinking Water Treatment Placement in the Context of Existing Infrastructure," Journal of Water Resources Planning and Management, 145, 11, November 2019. Available at: https://ascelibrary.org/doi/full/10.1061/%28ASCE%29WR.1943-5452.0001111

[4] Lund, Ibid.

[5] Lund, Ibid.

[6] Lund, Ibid.

[7] Lund, Ibid.

SD models also help drive allocation decisions between competing water needs, and achieving consensus among users for proposed near-term water supply plans.

SD models include water sources, users, recharge facilities, water and wastewater treatment plants. Simulations help planners understand the structural interdependencies of various elements in an end-to-end water supply and delivery system. It enables relatively realistic hypothetical system outcome simulations over long planning horizons.[8]

Contemporary simulations are yielding new results that have implications for longer term water supply planning for all water utilities. For example, construction of small-cluster decentralized wastewater treatment systems appears to be more economical than centralized plants when communities are spatially scattered or located in geographies with steep areas, where pumping costs may be challenging.[9]

1.2.3 Modeling tools for water supply planning must fit specific cases

In addition to systems dynamics modeling, linear programming, regression models, and various forms of sensitivity analysis applied to them afford water planners a robust array of tools. One of the challenges stemming from this robust array is how to integrate them or the extent to which they need to be integrated.

Models for addressing hydrological challenges, wastewater, storm water, and drinking water can be complimentary but cumbersome to run in parallel. Thus, integrating tools are available that can leverage "categorical models," including[10]:

- ***Location and geography as key integrating factors in water supply analysis.*** For example, city expansion often advances into rural areas creating dispersed and fragmented delivery patterns, which make providing water, gas, and electricity services more costly and often more difficult.

- ***Economic cost analysis of needed investments to meet service demand and the environmental costs associated therewith —*** especially for dispersed towns and small cities, which have higher population concentrations.

- ***Assessment of CI integration requirements,*** i.e., cities and regions experiencing expansion of dispersed locations often seek integration with higher density places for critical

[8] "Simulations" are different from "Scenarios." Simulations are model runs that product outcomes based on how assumptions and interdependencies are set for a particular run. Scenarios are narratives that describe possible futures and the factors that yield them. When articulated as a storyline, scenarios provide context for simulations and guidance on how to shape them. The difference between a simulation and a scenario helps to differentiate quantitative and qualitative planning processes; where the interaction of scenarios and simulations illustrates how qualitative and quantitative tools both compliment and reinforce each other. The result is a more robust set of planning process and decision choices.

[9] G. Chung, K. Lansey, P. Blowers, P. Brooks, W. Ela, S. Stewart, P. Wilson, "A general water supply planning model: Evaluation of decentralized treatment," Environmental Modelling & Software 23 May (2008).

[10] Michele Grimaldi, Vincenzo Pellecchia, and Isidoro Fasolino, "Urban Plan and Water Infrastructures Planning: A Methodology Based on Spatial ANP," Sustainability, May 2017. Available at: sustainability 2017, 771; www.mdpi.com/journal/sustainability

infrastructure services. Uncertainties in the planning of infrastructure investments can lead to mis-sized actual delivery systems to meet dispersed demands for service (especially when the growth trajectories are volatile). Careful estimation of the location of infrastructure investments helps to guarantee not only economic savings but also reduce associated environmental costs.

- ***Creating links between infrastructure planning and overall urban planning*** can help to minimize inefficient capital deployment. Modeling robustness helps to inform investment decisions, but does not necessarily contribute to an end-to-end water supply/demand management plan.[11]

1.2.4 Capital investments, water supply modeling, desalination, and the water-energy nexus

Capital investments in water supplies are a dominant consideration for water utilities. Financial models must uptake results from systems models, infrastructure planning models, and in some cases urban planning issues, which are policy-based, not necessarily computationally articulated.

One particularly important "out of the box" consideration for water supply planning is the relationship between electric power and water supply. For example, optimal strategic and operational decisions for desalination-based water supply systems present more cost-effective outcomes when integrated with hybrid energy systems (wind, solar, battery combined with small gas-fired generators). In Perth, Australia, needs for desalination to secure water supplies for the city and its surrounding areas serve to enhance sustainable energy deployments. In combination, both desalination and renewable energy cost less than pursuing each separately.[12]

Importantly, water-electricity tradeoffs are emerging as new critical planning challenges. New modeling tools are emerging to support planning for and investment decisions pertaining to optimizing water-energy tradeoffs. For example, a two-level mixed integer linear programming model serves to highlight best fit hybrid energy-water pathways. Use of this model showed analytical results that helped to maximize operational flexibility through decentralized deployment of infrastructure assets. An integrated water supply system emerged from analysis, leading to a reduction in desalination costs of over AU $215 million.[13]

The mutually reinforcing water and energy needs in this Perth, Australia case produced 42 MW of higher solar cell uptake capacity on average in each of the planning year time horizons for Perth's desalination initiatives. Still, the determination of the best path depended on the selection of one particular option (scenario) as the preferred alternative — proceeding forward was highly dependent on the values associated with subjective criteria and the flexibility of operational and maintenance costs, which were challenges for conventional water utility operational practices. In other words, qualitative assessments were an important element in water supply capital investments.

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[11] Michele Grimaldi, et.al., Ibid.

12 Negar Vakilifard, Parisa A. Bahri, Martin Anda, Goen Ho, "An interactive planning model for sustainable urban water and energy supply," Applied Energy 235, 2019, 332-345.

[13] Vakilifard, et.al., Ibid.

1.2.5 Challenging water-energy tradeoffs and the contribution of renewable energy assets

Capital investment tradeoffs such as Perth encountered offer a peek into the much larger, mostly unprecedented, consideration of system scale interdependencies between water and electricity. Tomorrow's water supply planning will confront the implications of system scale interdependencies as climate change-driven droughts become more prevalent. Difficult choices between using water for cooling thermoelectric power production or for delivery to end-users likely will continue to amplify in significance.

Recent electricity supply failures in various locations of the world induced by drought events indicate that thermoelectric power production is vulnerable in new ways. This challenge is emerging when knowledge about implications is limited and policy gaps have yet to be identified and addressed at the scale of watersheds as sources of water for urban areas. Emerging water-energy nexus models focus on facilitating electric power generation decisions and environmental policy designs involving cooling water consumption and temperature controls for power production.[14]

Tomorrow's energy supplies may necessarily shift to sources requiring minimal water use for cooling. Power supply assets harvesting solar and wind are likely to be winning solutions; ironically making renewable energy choices compelling not only because they are cost competitive but because they help to ensure essential water supplies for cities and towns. Integrating battery assets into renewable supply configurations further enhances the renewable resource value proposition in the context of a water-energy nexus challenge.

1.2.6 Unprecedented water-energy optimization challenges and the value of scenarios

Overriding all water management decisions is a physical, hydrologic constraint that is a function of watershed supply and water system sourcing and delivery conditions. Investment tradeoffs and policy gaps at the interface of water and energy span two additional dimensions. First, there is an *unprecedented optimization challenge* in balancing water supply needs against the criticality of electricity supplies literally on a minute-to-minute basis. Second, there is *a tradeoff matrix to be developed that considers environmental impacts and potential electricity supplies at the power plant and watershed levels,* respectively. Policy parameters for addressing such tradeoffs are focused on combinations of environmental regulations and economic penalties during a drought event.[15]

While quantification of new challenges is vital for understanding their scope, scale, and implications, quantification is not the primary engine of policy decision-making under conditions of uncertainty. Certainly, it is an essential input; however, policies are shaped qualitatively as a function of the risk propensities of leaders and their related sociopolitical agendas. If for no other reason than this,

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[14] Water-energy issues are developed more thoroughly in Sections 5 and 6. Complexities in optimizing water and energy services stem from, in part, insufficient recognition of the importance of critical infrastructure interdependencies. Once appreciated, critical infrastructure planning supersedes core water and energy infrastructure planning to encompass longer term shifts in the way that power supplies are categorized, e.g., baseload erosion from market dynamics may drive baseload accretion for reliability assurance of water service systems during serious event disruptions. This will be discussed further in Sections 5 and 6.

[15] Mengfei Mu, Zhenxing Zhang, Ximing Cai , Qiuhong Tang, "A water-electricity nexus model to analyze thermoelectricity supply reliability under environmental regulations and economic penalties during drought events," Environmental Modeling and Software, 123 (2020).

contemporary uses of scenario design and planning are important add-ons to the mix of quantitative modeling tools used for water supply planning.

In Section 4, attention will turn to applying contemporary adjustments to scenario practices in service to water supply planning. It is important to journey into the relationships between quantitative modeling practices in water supply planning and qualitative tools, such as scenario design and use, before turning to how scenario tools can proactively enhance existing water supply planning efforts.

1.3 Federal water planning

At the Federal level, water planning is framed as policies and administrative rules to address national level problems. For example, Federal legislation frames water management challenges as conservation, recycling, pollution and water quality protections.

Federal actions date from the mid-1800s, including the 1899 River and Harbor Act which prescribed direct regulatory authority for the Corps of Engineers for monitoring, controlling, and/or prohibiting the dumping of dredged material and other debris into the nation's navigable waters. Other main Federal water legislation included the Federal Water Power Act of 1920, which established a uniform process for the licensing of private hydroelectric power projects, and the Flood Control Act of 1936, which specified terms and conditions under which the Federal government would become involved in flood control matters and the use of cost benefit analysis for evaluating investments.

Through the 1960s, Federal legislation on water matters focused mainly on flooding. For instance, the 1965 Water Resources Planning Act was passed as part of a continuing effort to coordinate and centralize federal water resources planning and policy formulation. The late 1960s through the 1970s saw the formation of environmental policies, creation of the EPA, water pollution control and wetlands protection, and endangered species.[16]

1.4 State and local water planning

Federal concerns are focused on flooding and pollution, as well as ecological impacts. State and city level water planning focus on everything from one end of the water supply chain (water sources) to the other end (water uses). Most state and city level water plans include the same components, although city level water planning is the most complex and diverse. While each plan is distinctive, most all plans include the following elements:

- Urban water supply from end-to-end examined using engineering and environmental models
- System water use by consumers
- Baseline and reference data on customers, trends, and uses
- System supplies
- Water supply reliability

[16] https://www.nap.edu/read/6128/chapter/3#18

- Water storage and contingency planning
- Demand management key performance indicators
- Information infrastructure
- Labor
- Financial and regulatory processes
- Consideration of contingencies (risks), which may impact water utility operations

1.5 Case examples, California, Texas, and Austin's 100-year plan

Two of the more contemporarily progressive state water plans come from California and Texas, and within Texas, the city of Austin's 100-year water supply plan is a distinctive achievement.

1.5.1 California

California Water Plan Update 2018 provides recommended actions, funding scenarios, and an investment strategy to bolster efforts by water and resource managers, planners, and decision-makers to address California's most pressing water resource challenges; including flood risk, more reliable water supplies, reduced groundwater depletion, and greater habitat and species resiliency. These challenges are being addressed understanding resource limitations and management deficiencies with a recognition that the organizing principles are (a) sustainability of outcomes, (b) greater public health and safety benefits, (c) economic health, (d) ecosystem vitality, and (e) socio-cultural integrity.[17]

1.5.2 Texas

Water for Texas is the statewide water plan for 2017, updated in 2019.[18] Its composition is comprehensive. Its focus leans toward water conservation and drought management. The elements of the plan include:

- *Drought and drought response* — including evaluation of prior droughts and how the state handled them.
- *Costs of the state water plan* discussed as financial requirements.
- *Future population and water demand* — including projects for demand by region, demand for municipal services, demand for manufacturing, mining, power generation, irrigation, and livestock, as well as discussion of uncertainties of water supply and demand forecasting.
- *Water supplies* — including surface water availability within river basins, future surface water availability, groundwater availability within aquifers, future groundwater availability within

[17] https://water.ca.gov/Programs/California-Water-Plan

[18] Available at: http://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf

aquifers, other sources and existing supplies, as well as discussion of uncertainties specific to assessing existing and future water supplies.

- *Water supply needs* — including existing needs, municipal needs, non-municipal needs, wholesale water provider needs, issues related to not meeting needs, uncertainty about future needs, and implications of needs that exceed those within the plan.

- *Water management strategies,* which focus on strategy design and framework and discusses options in general terms.

1.5.3 Austin, Texas

The city of Austin's recent 100-year water plan is arguably a breakout contribution to water strategy and supply planning. The rationale for and design of Austin's water planning effort is quoted below.

> "The recommendation to develop an integrated water resource plan emerged from the historic drought Central Texas endured from 2008-2016. During the drought, the lakes that supply Austin's drinking water fell to historically low levels. While Austin successfully weathered the drought, the event highlighted the need to increase the sustainability, reliability, and diversity of Austin's water supplies through an integrated water resource plan. Water Forward addresses these issues by modeling potential climate change effects on Austin's water supplies and evaluating multiple future scenarios to plan for droughts worse than what we have experienced in the past. The recommended plan is the culmination of a robust effort that involved the Austin community, the Water Forward Task Force, an outside consultant team, City staff, and others."[19]

Austin's 100-year water forward plan focused on major water supply projects and incremental demand management and reuse solutions, and on augmenting Austin's access to water during drought conditions, when core surface water supplies are severely limited

The plan, as noted, was born of severe drought for 2008-2016, which drove home the need for a plan that was resilient in the face of changing climate conditions and significant population growth. Table 1, on the next page, exhibits the Water Forward planned changes to ensure safe, reliable, and affordable water service to the city over the 100-year planning horizon.

Population growth, drought, and climate change were the main parameters of Austin's planning methodology, with significant stakeholder engagement underlying plan design.

[19] Available at: www.austintexas.gov/department/water-forward

Table 1-1. Water Forward recommended strategies with planning horizon yields

Option #/ Type	Recommended Strategies	Average/ Drought	Estimated Yield (Acre Feet per Year)[1]			
			2020	2040	2070	2115
	Demand Management Strategies					
D1	Advanced Metering Infrastructure (AMI)	Both	600	3,880	5,770	9,370
D2	Utility Side Water Loss Control	Both	3,110	9,330	10,918	13,060
D3	Commercial, Industrial, and Institutional (CII) Ordinances	Both	1,060	1,060	1,060	1,060
D4	Water Use Benchmarking and Budgeting	Both	-	5,950	11,670	25,230
D5	Landscape Transformation Ordinance	Both	-	3,040	7,430	15,050
D6	Landscape Transformation Incentive	Both	-	320	630	930
D7	Irrigation Efficiency Incentive	Both	40	210	430	390
D8	Lot Scale Stormwater Harvesting	Both	-	330	870	2,280
D9	Lot Scale Rainwater Harvesting	Both	-	1,550	4,030	9,250
D10	Lot Scale Graywater Harvesting	Both	-	2,130	5,620	12,670
D11	Lot/Building Scale Wastewater Reuse	Both	-	1,320	3,670	7,880
D12	Air Conditioning (AC) Condensate Reuse	Both	100	1,080	2,710	5,150
	Demand Management Strategies Sub-Total	-	4,910	30,200	54,810	102,320
	Water Supply Strategies					
S1	Aquifer Storage and Recovery	Drought	-	60,000	60,000	90,000
S2	Brackish Groundwater Desalination	Both	-	-	5,000	16,000
S3	Direct Non-Potable Reuse (Centralized Reclaimed Water System)	Both	500	12,000	25,000	54,600
S5a	Indirect Potable Reuse (IPR) through Lady Bird Lake	Drought	-	11,000	20,000	20,000
S5b	Capture Local Inflows to Lady Bird Lake (infrastructure also included as part of IPR, above)	Average	-	3,000	3,000	3,000
S7	Off Channel Reservoir	Both	-	-	25,000	25,000
S9	Distributed Wastewater Reuse	Both	-	3,150	14,470	30,050
S10	Sewer Mining	Both	-	1,000	2,210	5,280
S11	Community Scale Stormwater Harvesting	Both	-	160	240	500
	Drought Supply Strategies	-	-	71,000	80,000	110,000
	Average/Both Supply Strategies	-	500	19,310	74,910	134,440
	Water Supply Strategies Sub-Total	-	500	90,310	154,910	244,440
	Water Forward Recommend Strategies Overall Total		5,410	120,510	209,720	346,750
	Water Forward Recommended Implementation Strategies to Realize Estimated Yields Above					
	Phase 1 and 2: Water Use Benchmarking and Budgeting Ordinance					
	Phase 1 and 2: Alternative Water Ordinance					
	Expansion of Alternative Water Incentive					
	Phase 1 and 2: Dual Plumbing Ordinance Development					
	Ordinance to Expand Existing Centralized Reclaimed Water Connection Requirements					
	Current Supplies and Conservation					
	Colorado River and Highland Lakes Supply	Both	325,000			
	Drought Contingency Plan	Drought	Varies			
	Austin Water Conservation Programs*	Both	54,320			
	Centralized Reclaimed Water System	Both	3,960			

***Note:** Austin Water conservation program savings were estimated based on savings calculated during 2012-2015

***Table 1:** Exhibit of Austin, Texas Water Forward Strategies*

1.6 The use of scenarios in contemporary water supply planning

Scenarios are used in water planning to capture issues and challenges that may impact water planning but are not easily integrated into existing methods, models, and practices. They can account for uncertainties associated with climatic, socio-economic, and management conditions that affect the performance of water resource systems. These uncertainties can impact future water supply reliability, delivery, and water demand management, typically examined within the framework of contemporary modeling and analytical tools used by water planners. Notably, critical infrastructure interdependencies such as energy and water tradeoffs noted above may be only tangentially considered in core water planning practices.

The increasing interest in this nexus bears on water delivery reliability, among many other considerations. For water delivery to continue during forced outages of electric power, backup and/or primary onsite power sources must be integrated into ongoing water supply management and operations.[20] Doing so requires expert judgment on the extent of such redundancy and resilience. It impacts scale and scope, hence investment requirements for ensuring high level water supply reliability in these changing times.

Scenarios are more often applied as extrapolations from core quantitative models, for instance using Monte Carlo techniques for generating a wide array of best- and worst-case outcomes. These techniques benefit core planning by increasing the sophistication of and risk adjustments to water planning results. However, extrapolations by definition are locked into the underlying assumptions and limits of any modeling method. Scenarios are not similarly constrained.

Scenarios are descriptions of one or more future situations; they articulate possible events and outcomes; they serve as foils for assessing how the handling of present risks can lead to future consequences.[21] The transition from the present state of water supply and delivery in the US to a future state that is resilient and able to sustain quality water service under conditions of power supply duress is arguably a new challenge.

Water system models represent the complexity of interactions in combined processes from water sourcing to the delivery of water for end-use purposes. Water supply models focus on cost, reliability and affordability.

Scenario planning and multi-criteria decision-making can complement established water system analysis. Integrating scenario development, properly executed with methodology that fits existing water supply planning, allows for better problem structuring. It does so by focusing on relevant alternatives,

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[20] An important nuance is worth noting. Water utilities have backup power systems that secure system operations and ensure reliable service continues, even in cases of extended forced outages. Conventional water planning evaluates the cost/benefit of backup power supplies based on assumptions of what is normal and what the likely fan of "abnormalities" might include. Tradeoffs between costs of power supply and water supply availability and reliability tend to be less emphasized. Accordingly, optimization pathways that consider power supply cost variants under critical supply constraints merit increased attention. What is the best investment and operational framework if (a) water scarcity is the critical variable or (b) power supply reliability requires increased investment in long-term back-up power supplies to ensure water delivery reliability? Section 1.4 emphasizes the value of using scenarios to explore these more judgment-based planning challenges compared to conventional cases.

[21] Muhammad Amer, Tugrul U. Daim, Antonie Jetter, "A Review of Scenario Planning," Futures, 46 (2013) 23-46

external uncertainties, and appropriately configured evaluation criteria. Integrating appropriately shaped scenario development allows for a more thorough investigation of critical external uncertainties.

The key words are "appropriately shaped scenario development." There are many scenario development methods, each tailored for specific uses. For water planning, adding scenarios helps planners avoid stress testing particular assumptions in core quantitative water planning models for uncertainty parameters.[22] Finally, combining core quantitative planning models with appropriately shaped qualitative scenarios allows for a more balanced and objective evaluation of alternative water supply reliability pathways, in turn informing discussions among stakeholders. Better dialogues help increase acceptance of possible future investment and operational practices in service of continued high quality and reliability of service.[23]

Use of scenarios has been part of risk-aware planning for decades. Over the arc of its use, its greatest strength also is its greatest weakness. Scenario development cannot be standardized and produce relevant recommendations for inherently non-standardized planning circumstances; i.e., unique planning challenges of specific local, regional, and/or state level water supply reliability. Appropriately shaped scenario-development must be evidence-based; where the evidence is resident in existing planning models and practices of specific water utilities and policy-making bodies. It must explicitly map "contextual factors" that contribute to how engagement in scenario development itself can change perspectives of participating stakeholders.[24]

A review of water policy issues (discussed in Section 2 below) brings to the foreground the significance of "unknowns" that can potentially have substantial impact on future water service development. Policy issues are primarily socio-economic and climate impact concerns, which bear on whether water supply sources are inevitably bound for scarcity as demand continues to grow.

For instance, with the growth of population and economy, water demand from domestic, industrial and agricultural sectors will increase, resulting in more stress on limited, shared water resources. As greenhouse gas (GHG) emissions increase and global temperatures rise, precipitation patterns change which directly impacts specific water resource availability and irrigation water demand. Water quality and ecosystem stability issues are part of this constellation, as well.[25]

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[22] An important reminder: robust water planning models enable comprehensive scenario-based analysis within the framework of the model design. Monte Carlo simulations, for instance, are valuable tools that give water planners rich palettes of impact analysis through which outcome validation can be confidently confirmed. The emphasis here concerns qualitative factors that are not presently configured within the frame of robust water planning models. Qualitative scenario articulation, or storylines to consider as such scenarios often are referenced, give decision-makers perspective on modeling outputs and enable decision-makers to direct planners to explore or consider specific potential impacts. This enhances the ability of planners to run models in ways that strengthen decision-making and increase investor confidence in capital requirements for water system operational improvements and/or expansion.

[23] Tobias Witt, Marcel Dumeier, Jutta Geldermann, "Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios," Journal of Cleaner Production, 242 (2020).

[24] David Firth, Efstathios Tapinos, "Opening the black box of scenario planning through realist synthesis," Technological Forecasting and Social Change, 151 (2020).

[25] Congli Dong, Gerrit Schoups, Nick van de Giesen, "Scenario development for water resource planning and management: A review," Technological Forecasting and Social Change, 80 (2013) 749-761.

Assessing future impacts of climate change is subject to significant uncertainty, due to knowledge and data gaps on climate system behavior and its interaction with water systems. Water supply models projecting future precipitation and water resource availability are beginning to diverge on impacts and outcomes against water reliability and service delivery as objective functions.[26]

Divergence in water planning modeling platforms has inspired deeper dives into the significance of uncertainties at the root of modeling output divergence. These deeper dives help water managers and decision-makers take more robust decisions, which drive more relevant management strategies.

For example:

- A Water World Vision study focused on water availability and demand driven by population growth and GDP as critical underlying uncertainty factors.[27]

- A global water outlook study focused on precipitation and temperature changes as root causes of uncertain outcomes in availability of food, water, and agriculture supplies.[28]

- A study of water withdrawals and the effect on climate focused on foundational effects inherently amplifying critical uncertainties, including birth/death rates, GDP, water use efficiency, population growth, and land use.[29]

- Water availability and use with impacts on aquatic biodiversity impacting water supply focused on population growth and water use efficiency as underlying concerns is another example.[30]

Several additional studies are profiled by Dong, et.al., demonstrating the key uncertainties of critical water supply impacting variables.[31]

Another aspect of appropriately shaping scenarios for water planning is how planning processes themselves can influence, or bias, the value of adding scenario analysis to contemporary water planning models. Figure 1 below presents a generic scenario development process workflow.

Achieving useful, appropriately shaped scenarios for water planning requires (a) understanding the development process, (b) key flaws in it, and (c) tactics for increasing the value and integrity of scenario development directly tied to specific water supply planning cases.

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[26] Congli Dong, et.al., Ibid

[27] W.J. Cosgrove, F.R. Rijsberman, in: World Water Vision: Making Water Everybody's Business, Earthscan Publications, London, 2000, Available at: http:// www.worldwatercouncil.org.

[28] M.W. Rosegrant, X.M. Cai, S.A. Cline, "Global water outlook to 2025: averting an impending crisis," A 2020 Vision for Food, Agriculture, and the Environment, Initiative, International Food Policy Research Institute, Washington, D.C., U.S.A, 2002

[29] G. Gallopín, "Five stylized scenarios," United Nations Educational, Scientific and Cultural Organization, Paris, France, 2012.

[30] S.R. Carpenter, P.L. Pingali, E.M. Bennett, M.B. Zurek, in: Ecosystems and Human Well-being: Volume 2 Scenarios: Findings of the Scenarios Working Group (Millennium Ecosystem Assessment Series), Island Press, Washington, 2005, Available online at: http://www.watercouncil.org.

[31] Dong, et.al., Ibid.

Figure 1: *Typical Scenario Development Process*[32]

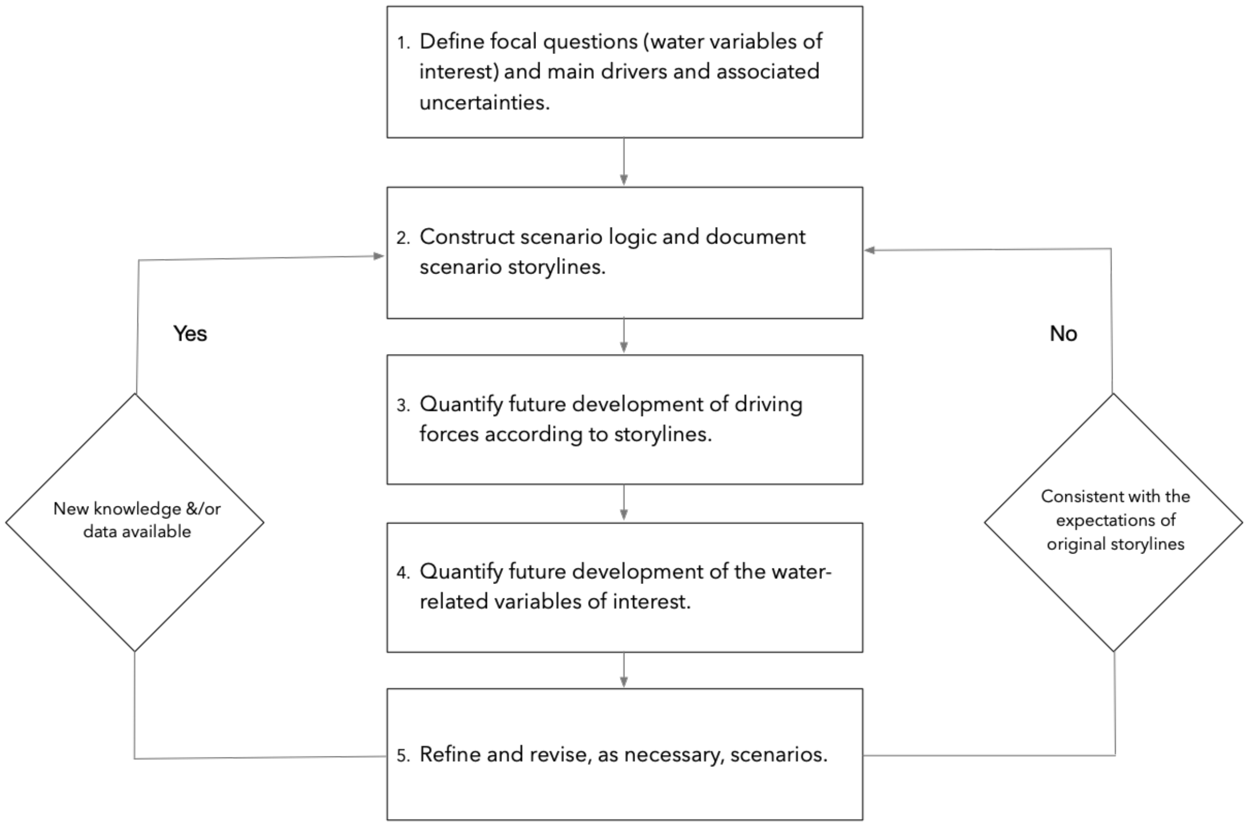

Figure 1 depicts a generic scenario development process that combines qualitative scenario development with quantitative model configuration. In the early phases of scenario methodology development, qualitative stories were the singular focus of the effort. Presently, most scenario processes integrate underlying computer modeling to quantify the impacts and implications of future storylines.[33] In the case of water planning, existing robust computational models can be adapted to align with qualitative story development and vice-versa.

The scenario development process itself is designed to be malleable. Scenario integrity depends on the quality of inputs, i.e., the SMEs and other participants in the story development effort such as local stakeholders, decision-makers, and scientists.

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[32] Adapted from diagram in Dong, et.al., Ibid.

[33] A stellar example of this can be found in UNECE scenario planning activities concerning decarbonization requirements under the Paris Agreement. The gateway into a very rich scenario planning system is available at: https://www.unece.org/energywelcome/committee-on-sustainable-energy/committee-on-sustainable-energy/energycommitteemeetings/committee-on-sustainable-energy/committee-on-sustainable-energy/2018/stakeholder-consultation-workshop-national-sustainable-energy-action-plans-scenarios-for-central-asia/docs.html

However, scenario relevance depends on the definition of the situation that frames the overall effort. For example, when a reservoir has to be designed in order to alleviate an unevenly distributed water resource, storylines to describe water shortage situations in dry years and water abundance in wet years are not sufficient to identify an optimal design for the reservoir. It requires integrating quantitative and qualitative planning tools.

Misconstruing scenario integrity for scenario relevance is a key flaw in the way scenarios generally have been applied. That is, the scenario planning tool cannot be applied effectively to a specific and granular question relating to reservoir design. A more appropriate framing would elevate the scenario process to framing choices based on future outcome storylines at the city, region, or state level encompassing water planning from end-to-end of its supply chain.

Other flaws in scenario planning that warrant attention include (a) limitations in the number of quantitative scenarios that can be considered, (b) implicit or incomplete characterization of uncertainties, and (c) lack of transparency when implementing expert judgment procedures.

However, each of these flaws also can be the basis for sound scenario development when recognized and incorporated into the generic process noted in Figure 1. Specifically:

1. ***Addressing the limited number of scenarios in typical scenario planning efforts***

   Legacy scenario planning processes tend to consider a handful of discrete quantitative variables, which are achieved by assigning numerical values to variables that map to qualitative storylines. However, contemporary modalities simultaneously build qualitative storylines and modify robust computational models relevant to the defined situation for which scenarios are being developed and applied.

   Critiques of legacy scenario planning processes emphasize that qualitative scenarios have limited value because only a few stories are crafted, e.g., business-as-usual balanced against extreme cases on the upside and downside.

   By contrast, *contemporary scenario design* processes are robustly crafted from deep analysis of the field pertinent to story development. For example, for water planning in an age of unprecedented change, the field must be defined as the whole supply chain and surrounding ecosystems impacted therefrom at the appropriate scale — typically appropriate scale is marked at a watershed or at a state level where policies can shape the overall water challenges that have cross-impacts on cities and intra-state regions.

   Contemporary scenario design also offsets notions of scenario distributions of upside and downside as bookends to an as-is case. First, it was recognized that a central as-is scenario will be selected more frequently when the options are either an extreme upside or downside case. Second, a matrix defined by two intersecting continuums eliminates selection bias based on case distribution. Also, this approach increases the linkage potential between qualitative and quantitative planning by enabling intermediate cases to articulate between bookends. Finally, a balance between parsimonious use of planning tools and a lavish use of scenarios for an extravagant number of purposes requires judgment from SMEs and the wisdom of leaders. Dong, et.al., make the point.

   > "The implementation of statistical tools and mathematical algorithms together with the increased computational capabilities facilitates the generation and utilization of the large

set of scenarios. For example, Monte Carlo applications routinely involve millions of model runs, where each model run essentially represents a different scenario. Scenario discovery algorithms classify a wide range of scenarios simulated by hundreds to millions of model runs into multi-dimensional regions, and select regions of interest reflecting the performance of policies for decision-support application. In order to design robust strategies to narrow the water supply–demand gap in California up to 2030, 500 different future states of water supply and demand were sampled from a large set of plausible future states to evaluate new supply/efficiency signpost policies by using scenario discovery algorithms."[34]

The implication of the above is that ensuring the best fit of scenario and computational based planning tools ultimately depends on (a) the purpose for which these planning tools are used, and (b) the wisdom of decision-makers using them.

2. ***Addressing incomplete and implicit uncertainty characterizations***

Legacy scenario planning practices tend to consider each scenario across a distribution to be equally likely — even when tendencies to select the mid-point as-is option over upside and downside extremes prevails. Contemporary techniques offset for these tendencies by how scenarios are constructed to ensure realistic contrasts between each. This was described in point 1 above.

Academics using scenarios may worry about drawbacks from lack of explicit articulation of probabilities. It could lead to confusion as scenario users might assign their own probabilities or select scenarios intuitively, rather than objectively based on robust probabilistic depiction of possible futures. For example, by attaching probabilities to various scenarios, the weight that each scenario plays in developing water management plans is explicitly considered and quantified.

However, there is no such thing as unbiased or judgement free probability estimates. Probabilities depend upon the experience and expertise of individuals contributing to scenario design. Whether using one SME or several, probabilities invariably are inexact because valuation is implicitly a compromise, if not explicitly so noted. Of course, there are tools to shore up the integrity of probability estimates, e.g., axiom-based practices that check and limit subjectivity, or Bayesian probabilities that drive people to explicitly explain the judgments they make help to enhance integrity.

3. ***Addressing insufficient transparency around SME judgments***

There is a complicating factor when integrating quantitative and qualitative planning tools. If the integration process is not transparent, it leaves the integrity of analytical outcomes subject to question. What protocols were used in scenario design that guided the conversion of qualitative stories into quantitative modeling? Documenting as explicitly as possible the techniques that were used in scenario design helps with stakeholders and decision-makers who may question the integrity of scenarios designed and used.

Nevertheless, the proof of value is not in the precision of subjective judgments but rather in the integrity of judgments, which guide the design of stories that capture both extreme possibilities

[34] Dong, et.al., Ibid., p. 756.

and intermediate cases where alternative futures may be more likely to occur. Contemporary practices acknowledge the risks of bias and offset it through a number of techniques, including (a) ensuring a large population of diverse SMEs, (b) an effective process that keeps SME judgements from drifting outside the definition of the situation, which frames the scenario design effort and (c) its interconnection with water supply planning models used by specific locations, whether cities, regions, or at the state level.

1.7 Institutional water planning and volatile patterns of change

1.7.1 Multi-level planning is diverse and complex

Water planning in the US occurs at the Federal, state, and local (city and town) levels. Each level has complex institutional processes that occur with only partial alignment. For example, Federal clean water mandates leave some funding to state and local governments.

In addition to these three vertical planning structures, there are cross-cutting regional agencies, e.g., the Lower Colorado River Authority, with responsibilities for coordinating water planning and management at regional levels, connecting multiple counties within a state and water issues that cross state lines.

Institutional authority flows from Federal to state and state to city levels; requirements of cities and regions vary in scope and complexity. Local water management may involve multiple city departments. For example, a city's water utility may be required to coordinate with the city's transportation and public works entities if streets and sidewalks must be opened to address water utility delivery problems. Such coordination is both necessary and cumbersome; leading to delays in execution and long-lead times unless in an emergency.

1.7.2 Fiscal gaps

Fiscal gaps play an important role in sustaining, if not expanding, the need for more robust water plans. More robust plans can support financing system changes at scale over time, e.g., changes in water infrastructure may be easier to finance when multiple states join together in a shared effort to finance, deploy, and operate critical water infrastructure.

For example, in 2007, Texas voters approved a constitutional amendment authorizing the issuance of Economically Distressed Areas Program (EDAP) bonds to provide financial assistance for State Water Plan projects in economically distressed areas of the state. In 2011, enacted legislation and accompanying voter approval of a constitutional amendment authorized the Texas Water Development Board (TWDB) to issue GO bonds such that the aggregate outstanding principal amount of bonds issued for the DFund at any one time could not exceed $6.0 billion.[35]

1.7.3 Water supply models, narrow-cast scenarios, and budgeting for water services

At the present time, tools for water planning include conventional budgeting processes enabled by well-established quantitative water supply models. Supply models extend into out-years where an array of scenarios can be assessed to guide city, regional, and state water supply decision-making.

[35] Available at: https://www.lbb.state.tx.us/Documents/Publications/Issue_Briefs/3116_State_Water_Plan_2017.pdf

Out-year forecasts leverage core water supply models, which form the foundation of relatively narrow casted scenarios, i.e., extrapolations based on supply and demand assumptions, which drive water supply models and produce gaps requiring changes in supply management (e.g., drought mitigation) and/or demand management (e.g., conservation) practices. Such narrow cast scenario planning helps to enhance the robustness of quantitative forecasts, which support more thorough articulation of needs for infrastructure changes and related financing requirements.

1.7.4 Water planning through the lens of drought management

State policies governing droughts and floods place procedural, monitoring, and process requirements on cities. The terms may differ by state but states in drought-intense areas of the country set water management principles, which local governments and their water utilities are bound to follow. Xinyu Fu, et.al., analyzed US state-level drought policies on three main criteria — (a) hazard occurrence and frequency, (b) vulnerability (of biophysical and social domains), and (c) risk management, where planning practices and thoroughness were used as proxies for assessing state level drought management readiness.

Key findings showed most states benefiting from improved planning, however Colorado, Hawaii, California, Arizona, New York, Texas, Idaho, Montana, Rhode Island, Missouri, and Nebraska were best practice states. Notably, only eight states did not have a drought early warning system in place, and only twelve state plans listed financial sources for drought mitigation. Only California set specific water conservation goals. Texas stood out for its integration of early warnings, impact clarity, conservation targeting, and identifying funding sources to support city level water utilities.[36]

1.7.5 Critical infrastructure interdependencies are generally underemphasized

Cross impacts on other critical infrastructure tend to be under emphasized in water planning scenarios. Existing water supply models generally do not take these interactions into account, as previously exampled regarding water and energy. Also, social changes impacting both supply and demand can further enhance extrapolations from existing supply focused plans, but the focus on supply-demand gaps still remains.

These factors can be incorporated without having to alter existing supply models using a "nonlinear" scenario planning modality. Section 3 discusses scenario enhancements designed to complement existing tools.

1.8 Challenges facing water supply planning impacting all institutional levels

Recently, the Water Resources Foundation (WRF) prepared a report aiming to identify critical challenges these institutions will face. WRF identified seven main challenges:[37]

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[36] Xinyu Fu, Mark Svoboda, Zhenghong Tang, Ahi-jun Dai, and Janjun Wu, "An overview of US state drought plans: crisis or risk management?" Natural Hazards, 2013 (69) 3.

[37] Available at: https://www.waterrf.org/sites/default/files/file/2019-09/4949-IntegratedPlanning.pdf

1. *Politics and competing interests* — a perennial underlying consideration, which drives ensuring stakeholder engagement is ongoing

2. *Funding* — allocations amongst competing interests and prioritization between multiple critical infrastructures as ongoing friction points

3. *Water rights and regulatory hurdles — function* as barriers to change and reinforcers of the "as-is"

4. *Utility cooperation and coordination* — essential to executing changes, but "drag coefficients" on expeditious change management

5. *Public perception* — an essential force that can drive change or resist it

6. *Insufficient implementation tools* — such as asymmetric operational practices that enable quick responses as needed

7. *Insufficient experience with how to apply new water management tools — which* is consistent with a mature institution delivering reliable critical services facing a plethora of significant challenges requiring adaptation through changes in people, processes, and technologies

These main challenges reflect issues that policymakers and decision-takers must navigate in both today's and tomorrow's world. They are categories that are persistent across time. Their generality may serve policy matters while a deeper understanding of water planning issues is essential. How water planning can be enhanced with scenario "add ons" emanates from understanding the forces that are reshaping end-to-end supply chain management of water. Section 2 considers the issue landscape that informs operations and maps both problem definition and solution specification.

2. The Changing Water Planning Environment

In this section, attention turns to the evolving state of water supply planning. Its conventional methodologies are rooted in deep analytical and simulation modeling. The aim of these models is to provide water utilities and agencies[38] with tools to plan for capital improvements, expansion requirements, and overall water quality and allocation challenges.

2.1 Uncertainty and water resource management decision-making

Conventional water planning now integrates key elements in the end-to-end water supply chain where cross-impacts influence specific requirements or possible outcomes. Integrated water supply planning enhances risk analysis to improve the efficiency and effectiveness of water system management. It uses scenarios to assess impacts. However, scenarios in this case focus on statistical tools such as Monte Carlo analysis or various stochastic methods to improve the understanding of risks in service of better decision-making. Broader use of scenarios is less evident in most water planning processes.

One Water (integrated water planning) methodology is thorough and incorporates risk identification and mitigation. However, risk identification and mitigation are only one aspect of uncertainty that merits inclusion. Hart and Halden studied US city water plans, and state-level guidance postures on water supply and demand management related to drought, flooding, and climate change. Findings relevant to water planning in an age of climate change include:

- *Long-tails to mitigation programs.* Regarding state-level guidance supplementing Federally mandated flood mitigation requiring programs to be updated regularly — this occurs regularly only 54% of the time amongst the sample population of cities and states in the five years from 2013-2018, but 84% of the time over a ten-year horizon.

- *Outdated data.* Nevertheless, the underlying floodplain mapping data used for meeting program requirements relied on Federal Emergency Management Agency (FEMA) data, which was chronically outdated. FEMA drought planning guidance was the most outdated (only 16% was current in the last five years and 18% for the last two decades). Across the US almost universally (94%) reactive (emergency response) was the priority over proactive mitigation management.

- *Misalignments of data and guidance.* Although 79–94% of states provide some level of water supply and demand guidance, projections themselves tend to significantly predate guidance.

- *Climate change is not effectively incorporated.* About 70% of US states still lack climate change impact guidance, particularly non-coastal states and those impacted by increased water scarcity rather than flooding concerns.

[38] Water supplies are primarily municipal water utilities; in some cases there are regional authorities that govern water supply chains. At the state level, water supply and management responsibilities are vested in one or more departments. For purposes of this work, the term "water utility," or "water utilities" will be used to reference all forms of local and regional water supply entities.

- *Inelastic demand.* Strategies are rare (4%) for addressing the impacts of increased variability and uncertainty in meeting inelastic demands.

Hart and Halden state: "We conclude significant gaps exist in planning to address known or projected risks of climate-related impacts. Specific recommendations, including the implementation of a nationwide water census, are [needed] to improve both the data and knowledge base of water management and reduce current vulnerabilities.[39]"

2.2 The changing issue map and its implications

The following clusters of issues emerged from ISE's review of recent (2018-2020) water planning literature in scholarly journals.

1. *Supply planning,* including water storage, quality, recycling, and energy-water tradeoffs, as well as energy-water-food interdependencies. The parameters, scope and scale, as well as cross impacts present a different mix of challenges depending on water utility priorities, municipal policies, and the socio-economic changes caused by urban growth.

2. *Water allocation challenges,* including aging infrastructure and operations and maintenance costs. Important to note is the challenge of dealing with aging infrastructure applies to almost all states of the Union. Its relevance is further reinforced when the energy-water nexus is included as an interdependent slate of relationships, since electric power supply and delivery infrastructure also is aging out faster than replacement and upgrading investments can be made and deployed. Resistance to investing in both electric power and water infrastructure is centered on rate-impact concerns, but financial innovation typically is less emphasized than conventional bond and other utility financing instruments.

3. *Decision-making challenges,* including endogenous interlinked (e.g., how functions within a water utility coordinate and ration capacity) and exogenous interdependent influences (e.g., impact of energy supply, reliability, and costs on water supply and delivery costs, or necessary tradeoffs between water conservation as a sustainable solution to water scarcity or significant new capital investments to garner new water supplies from recycled or desalinated water). Which is more reliable? What is the value of high capital cost infrastructure for water reliability? How much lead time is required for conservation to mitigate shortages compared to new water reuse or desalinated water infrastructure? These and many other questions will impact conventional water supply planning decision-making — because what is happening to water supply planning is that the uncertainty parameters are increasing in complexity and interdependencies. Conventional water supply planning will need new tools for mapping both quantitative (e.g., systems costs and asset upgrades) and qualitative uncertainties (e.g., stakeholder interests, social equity, and environmental justice matters that are more difficult to quantify).

4. *Safety and security planning concerns,* in particular related to cyber infrastructure, such as smart water meters and SCADA (Supervisory Control and Data Acquisition) on water lines. Information

[39] Olga E. Hart, Rolf U. Halden, "On the need to integrate uncertainty into U.S. water resource planning," Science of the Total Environment, 691 (2019) 1262–1270

infrastructure, which enables smart meter and SCADA use-value, is costly and tends to require ongoing O&M, which includes upgrades to software platforms, such as CRM, ERP, workflow management, and web-based engagement channels. That is, once capital costs are incurred, a fast cycle of capital upgrades (computing power) and operating versions sustains this new infrastructure as essentially the critical infrastructure component of vital social and economic water services.

5. *Planning information* quality, accessibility, use-value, and privacy matters are important to keep up to date, especially related to population growth and how and where it clusters within an urban landscape. Existing water planning tools capture data but in some cases the data is old and the gap between the old and actual is significant enough to distort planning choices. This will be discussed more throughout the document.

6. *Processes,* which include planning activities related to resilience, reliability, and adaptation to changing circumstances, are mature for most water utilities. Inclusion of non-conventional processes may be necessary if a deeper integration of uncertainty issues must occur in water supply planning. For example, what would water planning look like if there was a surprising recession that reduced demand? What if population growth suddenly surged? What if aging infrastructure failed, disrupting service to parts of the system for sustained periods of time? How would water planning change if a severe drought was sustained for more than one or two years? What would happen if Federal mandates that were costly did not come with sufficient operating funds to implement them? These examples are intentionally simplified, but each case has cross impacts that can have ripple effects impacting other cities or regions, state water plans, and Federal compliance and enforcement of its mandates.

7. *Managing a stressed system,* especially in locations where water supply already is insufficient and urban population growth continues. The demographics and psychographics of population migration and settlement are important to map and track for many reasons. Consumer market segments use water differently, where pricing may or may not be effective at regulating use or allocating supply. For example, high income segments tend to use more water but also tend to be more aware of costs of water, so tiered, time-of-use, or real-time pricing regimes can influence consumption of higher income segments. By contrast, pricing regimes that exploit elasticity of demand tend to for quality of life choices for low income segments, i.e., pay the water bill or the doctor bill this month? In other words, the decision challenges related to water allocations can have far reaching impacts independent of sustainability considerations; but when sustainability moves to center stage, economic justice, environmental justice, and transparent processes also take center stage. Doing so, a comparatively simple water supply planning and risk analysis process collides with a fan of uncertainties.

The above elements and their characteristics are discussed further below. One important item is the importance of critical infrastructure interdependencies in water system planning, and this will be discussed in Sections 5 and 6.

2.2.1 Water supply planning

The predominant focus of water planning is supply and how to ensure water is available to meet existing and growing needs. Thus, water supply planning robustly considers storage options, quality assurance and control, methods and techniques for water reuse, and some energy-water tradeoffs.

Energy and water tradeoffs. Presently, discussions of energy and water tradeoffs are evident in literature, trade sites, and city water plans. Water utilities and agencies have not aggressively intervened with regulators or municipal utility boards to make the case that water for energy versus water for public use is becoming an unequivocal zero-sum game.[40] However, the time for such intervention is just over the horizon in many locations, in particular California, Arizona, and Texas, if it is not here already.

Hyperion example. Supply considerations overlap matters related to planning processes because the arguments for public use of water over its use for power production have to do with long-term resilience, adaptive flexibility, and hydro socio ecological tradeoffs. For example, the Hyperion project in Los Angeles brings to the foreground zero-sum tradeoffs between water for public use and its use for energy production.

The city of Los Angeles and its department of water and power is pursuing a large-scale initiative that will help meet the need for a resilient and independent water supply for Los Angeles — the Hyperion Water Reclamation Plant intended to replenish the city's groundwater basins. The Hyperion Water Reuse and Resiliency Program will help the city's 2019 Green New Deal goal to recycle 100% of available treated wastewater for beneficial reuse from Hyperion by 2035.

This new independent water supply will reduce L.A.'s reliance on imported water that must travel hundreds of miles and is vulnerable to drought, earthquakes, climate change and other natural disasters. By replenishing groundwater aquifers in Los Angeles, the program will potentially meet up to a third of the city's water demand.

The Hyperion Water Reuse and Resiliency Program is a partnership among LADWP, Los Angeles Bureau of Sanitation (LASAN), the Water Replenishment District of Southern California (WRD) and Metropolitan Water District of Southern California (MWD). Currently in the planning stages, the program has four key components:

- The retrofit of existing Hyperion assets with advanced treatment facilities producing up to 170 million gallons per day of purified recycled water.
- The aim is to convey this purified recycled water into underlying aquifers within the West Coast and Central Groundwater Basins to utilize up to 450,000 acre-feet of available storage.
- LADWP will pump the groundwater for distribution into the potable system, and it will construct a new pipeline to the San Fernando Valley to replenish the San Fernando Groundwater Basin.
- Water may be conveyed to the Los Angeles Aqueduct Filtration Plant (LAAFP) and the Metropolitan Water District's Regional Recycled Water Program's Backbone System.[41]

In the decades to come, other jurisdictions will be challenged to use novel methods to increase water supplies as Los Angeles' Hyperion project aims to do. Ground water restoration is a significant element in long-term resiliency planning for high quality, affordable and reliable water supplies, but groundwater

[40] These are findings of the authors based on review of city and state water plans as well as academic literature and trade press.

[41] https://www.ladwpnews.com/hyperion-water-reuse-and-resiliency-program/

is not the only supply challenge. For instance, Houston, Texas is considering desalination projects on its coastline with the aim of being able to meet growing demands for high quality water for the city.[42]

Today's water planning for tomorrow's needs must examine water supply with a much broader palette. Certainly, conventional water supply modeling can identify and explore various innovations for meeting forecasted water needs. However, in Texas (and California), desalination is far from being a consensus solution to worrisome water shortage possibilities. Robust scenario planning tools can help to clarify the implications of various choices for how to meet water needs in coming years. This will be discussed further in Section 4.

2.2.2 Water allocation challenges

Stresses on water supply systems intensify decision-making, which determines the allocation of water services for commercial, industrial, agricultural, and public water consumption purposes. Water allocation processes differ based on whether pricing, auction and trading, or needs-based criteria serve as the optimization function. Water rights and supply control complicate shifts in allocation processes and status quo use patterns, which become vital mechanisms for meeting water needs of local or regional service boundaries.

Particularly important reallocation requirements just over the horizon concern the significant volumes of water used by power plants for cooling and other purposes, noted in Section 1.0. Coal-fired and natural gas-fired generation are especially vulnerable to water reallocation requirements based on water supply reserves in coming decades.

Carbon-fueled electric power production is under siege from parties determined to end operations as part of large-scale decarbonization requirements for mitigating climate change. Water supply shortages and supply risk management may well overtake decarbonization advocacy as the primary driver of carbon-based generation asset closures.

For locations where power plants and fuel sources reside in the US, carbon-based generating assets may close, in turn liberating dedicated water supplies for other uses, e.g., agriculture and industrial requirements. Water planning in an uncertain world is significantly impacted by the potential for surprising causes of either increased water supply or intensified water scarcity from interdependencies thus-far not generally included in integrated water planning methods.

2.2.3 Decision making issues

Water utility strategic planning is rooted in the present state, engages present state leaders, and characterizes enterprise vision and mission with signifiers intended to speak to all perspectives by avoiding the concrete in favor of the abstract. For example, below is the mission statement of Los Angeles Department of Water and Power.

> The Los Angeles Department of Water and Power (LADWP) provides our customers and the communities we serve safe, reliable and cost-effective water and power in a customer-focused and environmentally responsible manner.[43]

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[42] Peter M. Lake, Kathleen Jackson, and Brook T. Paup. The Future of Desalination in Texas: 2018 Biennial Report to the 86th Texas Legislature on Sewater and Brackish Groundwater Desalination, Texas Water Development Board, December 1, 2018; available at:https://www.twdb.texas.gov/innovativewater/desal/doc/2018_TheFutureofDesalinationinTexas.pdf?d=1546638725773

[43] https://www.ladwp.com/ladwp/faces/ladwp/aboutus?_adf.ctrl-state=o1ndmibkm_4&_afrLoop=96449344266555

What does it mean to provide safe, reliable and cost-effective water? What does it mean to be customer-focused and environmentally responsible? How aligned are words and actions?

The assertions enable each stakeholder, whether internal to and external from LADWP, to internalize meaning within their own experiential context. Safe, reliable, and cost-effective might mean to a financial leader that rates should reflect the level of investment the agency deems appropriate (against what other stakeholders may think). To an operations person, the same terms may mean assiduous attention to water quality from reservoir to tap at whatever cost it takes to make sure that there is no risk or liability to the agency and no risk of damage to customers and their premises.

The reliance on such signifiers tends to increase customer and community mistrust of the utility or agency responsible for water delivery.[44] Lower trust makes public water planning more difficult to do. Rate increases emanating from water planning can be met with consumer resistance and political blocking.[45] Long-term service reliability is less assured when rate adjustments are diminished by cautionary political decision-making.[46]

2.2.4 Safety and security planning for water systems

Safety and security have two main priorities — protecting against cyber-attacks and mitigating physical and ecological risks.

Cyber. The smarter critical infrastructure systems become, the more complex the security needed to protect them. Cyber security issues are emerging as more smart meter assets are deployed and the sophistication of Supervisory Control and Data Acquisition (SCADA) assets continues to increase. Water planning will need to increase consideration of how smart assets can be attacked and damage the essential service of water delivery. In turn, this has implications for cost of service and quality of water delivered.[47]

Physical and ecological risks. The physical and ecological side of safety and security issues have to do with impending impacts of saltwater incursion and the need for including issues related to sea level rise in resiliency planning.[48] Adding an emphasis on resiliency in water planning improves the linkages between natural, ecological, and built environment spheres. It adjusts the planning focus to include water supply diversification, demand management, and ecosystem rehabilitation.

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[44] Marco Dettori Antonio Azara, Erika Loria, Andrea Piana, Maria Dolores Masia, Alessandra Palmieri, Andrea Cossu, Paolo Castiglia, "Population Distrust of Drinking Water Safety. Community Outrage Analysis, Prediction and Management," International Journal of Environment Research and Public Health, 2019 Mar; 16(6.

[45] Water prices are tracked by Circle of Blue, which informs stakeholders of water rate impacts. Available at: https://www.circleofblue.org/waterpricing/?gclid=Cj0KCQjw-Mr0BRDyARIsAKEFbee8u3IbHX1uHu7CTifswdnp1oPVQcxVr1ZQ_-TQhhbtkjw1vJuFcDAaAlbEEALw_wcB

[46] Observations based on authors professional experience.

[47] Available at: https://www.epa.gov/sites/production/files/2018-06/documents/cybersecurity_guide_for_states_final_0.pdf

[48] Rasoulkhani, et.al., Ibid.

Climate hazards increase uncertainty factors in several ways.[49] For example: obsolete data hinders effective anticipatory planning for water supply and delivery challenges. Flood planning is ineffective if data on floods, trends, and related urban impacts are not contemporary. The same applies to drought planning, water supply/demand forecasting, and relevant guidance for local water utilities from state-level water management functions.

Adaptation goes hand-in-hand with resilience planning; each complements the other. However, resilience planning and adaptation efforts are distinctively different matters when it comes to cost. Planning efforts are far less costly than necessary adaptive steps required as a consequence, such as building sea walls or upgrading wastewater systems to deal with back flows from saltwater incursion.[50]

Uncertainty in water planning can lead to greater costs of financing necessary adaptive investments. But humanity is unequivocally moving into a fundamentally altered state of the Earth's climate and ecosystems.[51] Core critical infrastructure is particularly vital to maintain and enhance as Earth's climate continues to change. Water storage and water reuse technology innovations are on the horizon, but their arrival will further disrupt conventional and contemporary water planning methods and practices. Integrated water planning methodology must evolve to stay relevant as the underlying dynamics of water supply and demand systems continue to confront surprises offered up by a changing Earth. Integrated water planning must become part of a larger critical infrastructure planning framework.

2.2.5 Planning information

Core metrics. Conventional water planning requires core data on operational Pressure Metrics of water systems and State Level Metrics for policy implementation. Both provide a platform for assessing present state supply and demand and enabling inputs into various water planning models (discussed in Section 1).

KPIs. Development planning data can be rolled up into one or more indexes, which help water managers track system status, identify and flag operational problems, and prioritize critical water sourcing and delivery challenges. Planning information also includes Key Performance Indicators (KPIs and/or benchmarks) for hydrological conditions, infrastructure integrity, and how urban water management can adjust to address trends in social behavior.[52]

Demand forecasting is included in conventional water planning, but the fan of possible demand forecasts can be influenced by uncertainties that are not easily quantifiable. For instance, demographic information on population growth is accessible; but robust information on settlement clustering and

[49] Kavita Hegn & Whitney Winsor, Climate Risks to Water Utility Built Assets and Infrastructure: A synthesis of interviews of national and international water utilities, Portland Water Bureau, City of Portland, September 30, 2015. Available at:https://www.wucaonline.org/assets/pdf/pubs-asset-infrastructure.pdf

[50] O. Marinoni, P. Adkins, S. Hajkowicz, "Water planning in a changing climate: Joint application of cost utility analysis and modern portfolio theory," 26 (2011).

[51] Olga E. Hart, Rolf U. Halden, Ibid.

[52] American Water Works Association, 2019 State of the Water Industry Report, Available at:https://www.awwa.org/Portals/0/AWWA/ETS/Resources/2019_STATE%20OF%20THE%20WATER%20INDUSTRY_post.pdf

characteristics of in-migration from other locations tend to be left outside the typical confines of water supply planning.[53]

Aging infrastructure is a capital asset. The state of degradation inherent in depreciation of assets is not as easily calculated. Utility managers tend to bet that another year or more can be squeezed out of assets before replacement is required. This perspective is consistent with conventional water supply planning; a weakness in planning is the degree to which "another year" being eked out of an asset is not stress tested either within a planning model or by modeling physical asset performance for purposes of predictive and preventive maintenance. The consequence of over playing a hand on the marginal extension of an asset life could yield significant system failures and unexpected and unplanned costs. Contemporary concerns over water quality as well as supply integrity would be enhanced if such uncertainties were factored into planning processes and analyses.[54]

2.2.6 Planning processes

Water planning is detailed, quantitative, and focused on models that help water managers make informed operating and investment decisions. Water planning tends to focus on critical issues; something all planning efforts do, but not done with great attention to critical infrastructure segments of economy and society.

Droughts and floods increasingly influence planning considerations. Questions of present state resilience and future state resilience requirements for water supply chains are growing in significance. Resilience may have distinctive features; but reliability of supply and delivery also is growing in significance. This is in response to increased stress of urban water systems (physical demand and aging physical infrastructure) and statewide water management requirements.[55]

In Texas and California and many other states, drought planning and mitigation is an important water supply challenge. Water planning processes integrate robust quantitative models, which cover spatial and economic geographic matters and engineering economic analyses. They examine possible outcomes using stochastic and/or algorithmic analytics. Results become decision-ready when options and tradeoffs can be clearly articulated for consideration by decision-makers.[56]

Resilience. On the one hand, planning models are used to examine how long-term resilience might impact water supply and demand; and similarly, provide guidance on what elements of water plans

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[53] Praveen Vija, Bagavathi Sivakumar, "Performance comparison of techniques for water demand forecasting," Procedia Science and Computing, 14 (2018) 258-266.

[54] PEW, How Development of America's Water Infrastructure Has Lurched Through History: And why we may be at another key turning point in the safety of public water. March 3, 2019. Available at: https://www.pewtrusts.org/en/trend/archive/spring-2019/how-development-of-americas-water-infrastructure-has-lurched-through-history

55 Kevin Werner, Lina Svedin, "States, water, and climate: Who's planning for change?" Climate Risk Management, 16 (2017) 59–72; Zhang, C; Xu, B; Li, Y; et al., "Exploring the relationships among reliability, resilience, vulnerability of water supply using many-objective analysis," Journal of Water Resources Planning and Management, February 2017. See also: Richard M. Vogel and Ralph A. Bolognese, "Storage-Reliability-Resilience-Yield Relations for Over-Year Water Supply Systems," Water Resources Research, March 1995, 31(3):645-654. Also, Sangmin Shim, et.al., "A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems," Water, 7 February 2018

[56] Hart and Halden, Ibid.

must adapt to changed circumstances; also, what elements can be addressed only in a reactive manner.[57]

For example, long-term resilience may be enhanced for a water utility by maximizing the penetration of smart equipment (from meters to monitors of water flows through pipes). The higher the information granularity, the more thorough can be estimates of impacts, which must be anticipated and mitigated to maintain water service. However, information granularity is an underappreciated value-add.[58]

Aging infrastructure. On the other hand, long-term resilience may limit adaptive flexibility if infrastructure management – which involves addressing aging infrastructure challenges and investment requirements to meet forecasted demand growth – is unable to evolve as exogenous changes compel adjustments to operating behavior and capital investments.[59]

Anticipatory versus reactive plans. Reconciling contradictions may be suboptimal for both long-term resilience and adaptive flexibility. For example, long-term resilience might be increased by investing in expanded reservoir capacity in locations where climate change may reduce watershed production, but in doing so adaptive flexibility for how to diversify water sourcing may be constrained. The outcome might leave a water utility to default to its conventional modus operandi — functioning in a highly reactive manner.

In most water supply chains, rivers, watersheds, water basins, and groundwater resources contribute some share of total water supply for meeting existing and growing demand. How rivers, watersheds and basins are managed impacts overall water supply, flow rates, contaminants (organic and inorganic), and water quality. The degree to which water management begins and ends with environmental sustainability significantly influences the integrity of existing water supplies, thereby supporting increased adaptive flexibility and long-term resilience investments that are less rigid. In other words, river flows can play a critical role in both present state and longer-term water plans.[60]

One Water models do incorporate some level of scenario planning, usually captured as cases of enablement or disruption of existing plans. For example, a "techno world" scenario is devoted to examining the value of maximizing technologies that help minimize water demand and maximize water supply reserves. A "consensus world" scenario is one that robustly documents the institutional "As Is" state in which a water utility or agency functions. A "fragment world" scenario applies water planning models to consideration of outcomes if a region or urban environment is composed of uncompromising and distinct views of how water systems and services should work and deliver reliable service at low delivered costs.[61]

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[57] Kambiz Rasoulkhani, et.al., Ibid.

[58] The significance of information as a value creating factor of production is an increasingly glaring oversight evident across economic sectors, but particularly pertinent to critical infrastructures and their interdependent impacts. Go-forward innovations in planning methods would be well served by understanding the value of information granularity and training water planners on its both its use and its economic value.

[59] John W. Kane, "Investing in water: Comparing utility finances and economic concerns across U.S. cities," Brookings, December 2016.

[60] Richard N. Palmer and Kathryn V. Lundberg, Integrated Water Resource Planning, no publication or date listed in the document.

[61] OECD Studies on Water, Managing the Water-Energy-Land-Food Nexus in Korea: Policy and Governance Options, 2018. Available at:
https://books.google.com/books?id=7EB7DwAAQBAJ&pg=PA110&lpg=PA110&dq=techno+world+scenario+water+planning&source

These modes of scenario planning fit well with existing models used for analyzing the state of water supply systems and the costs of expanding them to meet forecasted growing demand. They are analytically solid but tend to leave more qualitative characteristics out of scenario analyses. Hydro-socio-ecological (HSE) relationships are included in most plans but they tend to be more implicit than explicit. HSE relationships include how urban planning manages storm runoff. In some cities, runoff is fed directly from streets into rivers, contributing to ecological issues for river health and associated ecosystems. Social mores related to how toxic chemicals or materials are disposed of can have negative feedback on communities, as occurred in Flint, Michigan's water system lead poisoning.[62]

One Water enhancements could build on analytical scenarios to craft more distinctive "stories" of possible futures, giving decision-makers richer narratives to explore in service of better decisions.

2.2.7 Managing a stressed system

Water planning processes are designed to increase commitment to enterprise direction and practices, as are most enterprise planning activities. If internal commitment is not robust, execution is hampered. Less than effective performance can have ripple effects internally but also externally. If new billing systems are implemented but fail, institutional integrity is eroded internally; and greater emphasis must be placed on mitigating external reactions. Reactions extend to financial institutions, opportunistic stakeholder groups, and customers impacted by failed billing system modernization. These characteristics stem from an actual case, where the names of the entities involved cannot be included in the example.[63]

Uncertainty can savage existing operations. Climate hazard impacts, "Acts of God" such as earthquakes or hurricanes, and ecosystem changes that alter the sources and quality of water only amplify risks water managers must address. Limited experience in planning for a much broader and deeper definition of uncertainty disadvantages states and cities needing to prepare for significant changes in the built environment, e.g., seawalls, desalination plants, creation of navigable canals, renewable and resilient energy.[64]

These sorts of impactful uncertainties may alter long-term water planning and management whether water managers choose or do not choose to address them. Preparedness for longer term changes increases the probability of successfully navigating impacts.

Decision-makers will expect clarity in the articulation of uncertainties and impacts, but forthcoming issues related to climate change will not be easy to simplify for local decision-makers. New tools to aid water planning can bridge the gap between conventional processes and those that will be required to deal with uncertainty as an increasingly dominant consideration.[65]

=bl&ots=x5CI4gy5Rf&sig=ACfU3U1C8g3K3BXh66z4ZLyrrFrB3YwQqw&hl=en&ppis=_e&sa=X&ved=2ahUKEwj98Nmu3eXoAhWOj3IEHVGWAIkQ6AEwAXoECAwQMQ#v=onepage&q=techno%20world%20scenario%20water%20planning&f=false

[62] Michael M. Douglas, Sue Jackson, Caroline A. Canham, Bradley J. Pusey, Robyn Loomes, Samantha A. "Setterfield, Conceptualizing Hydro-socio-ecological Relationships to Enable More Integrated and Inclusive Water Allocation Planning," One Earth, November (2019) 1, 361–373.

[50] Tohid Erfani, Kevis Pachos, Julien J. Harou "Decision-dependent uncertainty in adaptive real-options water resource planning," Advances in Water Resources, 136 (2020).

64 Nicola Ulibarri and TylerA. Scott, "Environmental hazards, rigid institutions, and transformative change: How drought affects the consideration of water and climate impacts in infrastructure management," Global Environmental Change, 59 (2019).

[65] For example: Frederick Boltz, et.al., "Water is a master variable: Solving for resilience in the modern era," Water Security, 8 (2019).

3. Water Planning Under Uncertainty

Sections 1 and 2 focused on water planning issues and challenges, as well as quantitative modeling tools and qualitative judgment-based contributions to planning. This section briefly consolidates the main points of the preceding two sections.

3.1 Risk vs. uncertainty

Water planning literature distinctively distinguishes between risk and uncertainty. Risk may be generally characterized as probabilistic assessments of possible outcomes stemming from a change in operating practices or specific investments, e.g., a new trunk line or tunnel for water distribution. Probabilities may be articulated based on distinct definitions of success or failure. For example, the probability of investment loss offers a different risk assessment than the probability of asset failure within a wastewater treatment facility.

Risk is a vector-based calculation of outcome probabilities where numerous modeling tools are used to increase the robustness, or confidence, in the assessment of probable outcomes. Some methodologies include qualitative assessments from appropriate SMEs to enhance understanding of how models should be configured; then run to achieve the most robust findings, which support management and/or investment decision-making.

One promising novel approach for enriching the understanding of uncertainty in water planning is to use a combination of "preference elicitation" and "predictive modeling" to support core water supply planning models. A two-step elicitation process using online surveys and face-to-face interviews is followed by an extensive uncertainty analysis prior to integration with core water supply planning models.[66]

Uncertainty is a broader consideration of multiple risk profiles and cumulative impacts under various operational scenarios. For instance, uncertainty in water supply planning uses models to identify plans that either perform well under a wide range of plausible future conditions (via robust decision-making) or reflect adaptive management practices that rely on progressively adjusting plans as new information becomes available. The first approach is oriented around investment decision sensitivities that are indifferent to the actual source of uncertainties. Adaptive methods are optimally activated, delayed, and/or replaced to meet supply and demand gaps that emerge.[67]

Water planners use both frameworks when considering water supply investments and/or operational changes; where staged water infrastructure capacity expansion optimization drives plan, flexibility shaped by uncertainty.[68] But it is important to appreciate the emphasis with respect to how uncertainty is characterized, analyzed, and incorporated into water management decision-making.

- It is primarily model driven, i.e., starting with models rather than upfront articulation of risks as discrete or multi-attribute phenomena.

[66] Lisa Sholten, et.al., "Tackling uncertainty in multi-criteria decision analysis – An application to water supply infrastructure planning," European Journal of Operational Research, Volume 242, Issue 1, 1 April 2015.

[67] Erfania, et.al., Ibid.

[68] Erfania, et.al., Ibid.

- It is focused primarily on water supplies, their acquisition, storage, treatment, and delivery infrastructure.

- It is rooted in technical engineering platforms that provide extraordinary detail on how water assets are intended to perform against how they actually perform.

Thus, uncertainty can be said to be more narrowly focused and imminently understandable through a diverse array of modeling platforms. Recent platform innovations include interval-fuzzy information associated with flexible constraints and integrated interval joint probabilistic stochastic programs.[69]

3.2 Qualitative - quantitative complementarity

Preference elicitation with water planning SMEs works well for covering uncertainties related to marginal value changes amongst various supply investment options. In product marketing, "preference elicitation" occurs using conjoint analysis where options pertaining to a specific product profile are offered to prospective consumers. Analyzing the tradeoff decision-making of buyers helps product designers tailor offerings to fit specific consumer demographics. A similar process occurs when applying preference elicitation to water management. Is a back-up power system using diesel that controls emissions more cost-effective and reliable from an operating perspective than a gas-fired combined heat and power unit? Additionally, skillful use of preference elicitation can increase the robustness of (economic) utility functions, which do influence decision choices with respect to prioritizing water supply investments.

Issues of sustainability and "green growth" have become important factors in water planning. The dimensions of uncertainty have shifted to more robustly integrating environmental risks into modeling and planning processes.

Predictive modeling is enriched by preference elicitation regarding future socio-economic development scenarios. Scenarios in this case mean rigorous sensitivity analyses within water supply modeling platforms.

Sholten, et.al., analyzed 11 water supply alternatives ranging from conventional water supply systems to novel technologies and management schemes for sustainable water infrastructure planning in Switzerland. Four future scenarios were derived from 11 water supply alternatives. Ten diverse stakeholders were engaged to assess scenarios and recommend decisions. Results showed that preference elicitation integrated into predictive modeling helped identify best and worst-case solutions.[70]

Deep uncertainties. Water resource planning and design problems, such as sequencing water supply infrastructure deployment, are influenced by what is defined as "deep uncertainties." These are less technical factors with outcome fans that have much broader implications. For example, incorporating

[69] X.X. Ma, et.al., "An interval joint-probabilistic stochastic flexible programming method for planning municipal-scale energy-water nexus system under uncertainty," Energy Conservation and Management, Volume 208, 15 March 2020.

[70] Lisa Sholten, et.al., "Tackling uncertainty in multi-criteria decision analysis – An application to water supply infrastructure planning," European Journal of Operational Research, Volume 242, Issue 1, 1 April 2015.

population dynamics and the impact of climate change are deep uncertainties that can influence more narrowly modeled capital and operations planning.[71]

To handle such uncertainties, robustness can be used to assess system performance, but its calculation typically involves many scenarios and hence is computationally expensive. Consequently, robustness tends not to be included as a formal component of water planning models. However, there are new modeling techniques, i.e., "meta-models" which are lower cost and faster to use by essentially sampling from complex simulation models to achieve indicative outcomes.[72]

3.3 Water-dependent tradeoffs

Water is increasingly core to large-scale planning related to energy, food supplies, economic growth, and urban development.[73] The clarity of risks is enhanced by understanding complex systemic factors impacting water planning. "Systemic complexity" shapes overall uncertainty. It heightens the value of various modeling techniques for decision-makers. Preference elicitation from SMEs may improve the robustness of analyses, but the qualitative side of uncertainty can be improved to help facilitate decisions being taken.

Managerial and policy-maker decision-making is informed by analyses, but tradeoffs that must be made to achieve balanced water allocations, for instance, occur within the realm of experience-based judgment and the exercise of leadership. These qualitative domains are empowered by socio-political processes where compromise often achieves outcomes that work, even though resulting decisions deemed to be suboptimal by competing constituencies.

One concern is whether conventional compromise decision-making will remain effective as water supply and demand imbalances become more pronounced. Amendments to scenario processes and products can help decision-makers anticipate rather than merely react as the bases for compromise become more challenging. The city of Austin's 100-year water plan is exemplary for how it integrates the quantitative and the qualitative.

3.4 Story, narrative, and leadership

Effective decision-making depends on the quality of supporting analysis provided. Socio-political narratives that are rooted in solid qualitative and quantitative planning outcomes can help diverse stakeholders appreciate decisions made through the use of story-telling.

Narrative and story are part of a scenario toolkit, which defines and uses scenarios to paint pictures of outcomes of varying positive and negative characteristics. Such scenarios significantly enhance leadership decision-making and provide immediate capabilities for explaining in relatable ways why specific decisions were taken compared to other options.

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[71] Eva H.Y. Beh, et.al., "Robust optimization of water infrastructure planning under deep uncertainty using metamodels," Environmental Modeling and Software, Volume 93, July 2017.

[72] Eva H.Y. Beh, et.al., Ibid.

[73] Louise Gallagher, "Embracing Risk, Uncertainty and Water Allocation Reform When Planning for Green Growth," Aquatic Procedia, Volume 6, August 2016.

4. Scenario Planning

Scenario planning is particularly useful for identifying and mitigating longer term challenges, such as water supply risks in states of the southwestern US. Properly done, scenarios inform the development of early warning indicators. In the case of water planning, early warning indicators can help focus concerns over water supply as well as use conditions. These can be applied to proactively (and possibly preemptively) address changing supply risks. In turn, scenarios are helpful tools for anticipating policy changes that may be needed to ensure water supply and delivery systems are meaningfully adaptive to both anticipated and unanticipated changes.

In this section, add-on scenario planning techniques are discussed. Illustrative examples are offered regarding scenario development content and processes.

4.1 Use-value of scenario planning

Early warning indicators are a distinctively valuable work product of scenario development. Also, scenario planning gives budget constrained jurisdictions flexibility in the use of conventional and contemporary water planning models. That is, the use of models is informed by scenarios, which enables a more parsimonious and focused application of models, in turn reducing modeling and related advisory costs.

Scenario planning processes enable and empower greater focus on technology solutions and how solutions are adopted and deployed. State level and local level water policy options can be shaped to "bracketed risks" identified through scenario development processes.

For example, risks of degraded water purification and filtration technologies from aging and poorly maintained infrastructure might be identified for upgrading. Doing so may help reduce operating costs if UV applications can be deployed using very low cost renewable solar power.

Once scenarios are developed and accepted for use in water planning, they can be accessed for improving KPIs on early warnings of emerging water supply risks. Similar KPIs can be crafted for early warnings of unexpected changes in demand (either up or down).

4.2 Scenario framework for states

Any state with uncertainties pertaining to longer term supplies in the face of longer-term growth trends can benefit from adding scenario planning (stories and narratives) to existing state and local water planning practices, even if narrowly cast scenarios already are in use.

Texas' publicly available water plans show a consistent updating to remain contemporary, the latest update being 2017[74]. However, like most states, Texas water planning predominantly focuses on water sources and supply and how to maintain supply and demand balance over time. Using broader scenario planning techniques may bring more clarity regarding contemporary and possible forthcoming

[74] https://www.twdb.texas.gov/waterplanning/swp/index.asp

uncertainties and their interdependencies impacting state and local level plans. In turn, such clarity could alter the underlying assumptions that drive water supply planning, and hence influence the outcomes of water planning analysis.

For example, climate change, sea level rise, and thermally derived changes in water quantities in rivers might lead to consideration of desalination from a novel perspective, i.e., that it may contribute to mitigating sea level rise as it mitigates water supply scarcity. Captured in a scenario, desalination becomes an opportunity (or threat, depending on point of view) that can be examined long before decisions-must be made. It can be looked at as a current technology solution or examined as a future solution if technology innovation overcame sensitive social and environmental policy hurdles.

4.3 Illustrative schedule for scenario planning processes and deliverables

Scenario planning draws upon trends to inform various analytic regimes, e.g., qualitative storylines, quantified within the context of funding parameters, and integrated into the process of composing scenarios. Key inputs include supply, demand, technology mix, capital and operating costs, and relevant “climate budget” factors, e.g., contingency cost estimates for dealing with surprise such as anomalous hurricanes, heat storms, or excessive rainfall.

When trends and analysis are combined, scenarios can be articulated and implications evaluated. For example, adaptive policy options and implications within water policy spheres and water cross-impacts with other sectors (energy and agriculture) can be crafted to enhance decision-maker understanding of best- and worst-case outcomes.

Once scenarios are formulated, they can be tested using case studies of scenario relevant circumstances, policy directives, and associated outcomes. For example, if the One Water model informs scenario development, which delves into the impacts of sustained drought and materially reduced water supplies, examining actual cases of drought and supply risk mitigation (such as Australia, South Africa, parts of the US west where rivers no longer make it to oceans) may enhance the sophistication of water planning.

Technologies are increasingly impactful for managing water from literal source to literal sink. Innovations in filtration and water treatment, reuse, and supply chain energy cost reductions influence both the cost and quality of water supplies and service. Technologies for enhancing storage, like the Hyperion project of LADWP, and techniques for capturing and using storm water runoff also point to the long-term direction of end-to-end water supply chain management. Finally, technologies for desalination, solar and wind powered hydrogen extraction, and displacement of core energy costs of water systems with elements of low cost distributed energy sources contribute to overall water system resilience.[75]

Scenarios must include estimates of inbound but still over the horizon technology innovations in order to bracket both water system opportunities (for cost savings, resilience, etc.) and threats to sustainability, reliability, and quality. SME judgments on emerging technologies, their market and operational readiness as well as their impacts on existing systems are essential elements in scenario development.

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[75] Zhongwen Xu, Liming Yao, and Xudong Chen, “Urban water supply system optimization and planning: Bi-objective optimization and system dynamics methods,” Computers and Industrial Engineering, □□□142 (2020).

Figure 2 illustrates a generalized scenario development workflow beginning with trend identification, moving onto analysis (qualitative and quantitative) that informs the development of distinctly different but possible storylines, and finishes with deliverables, which include robustly articulated complete scenarios.

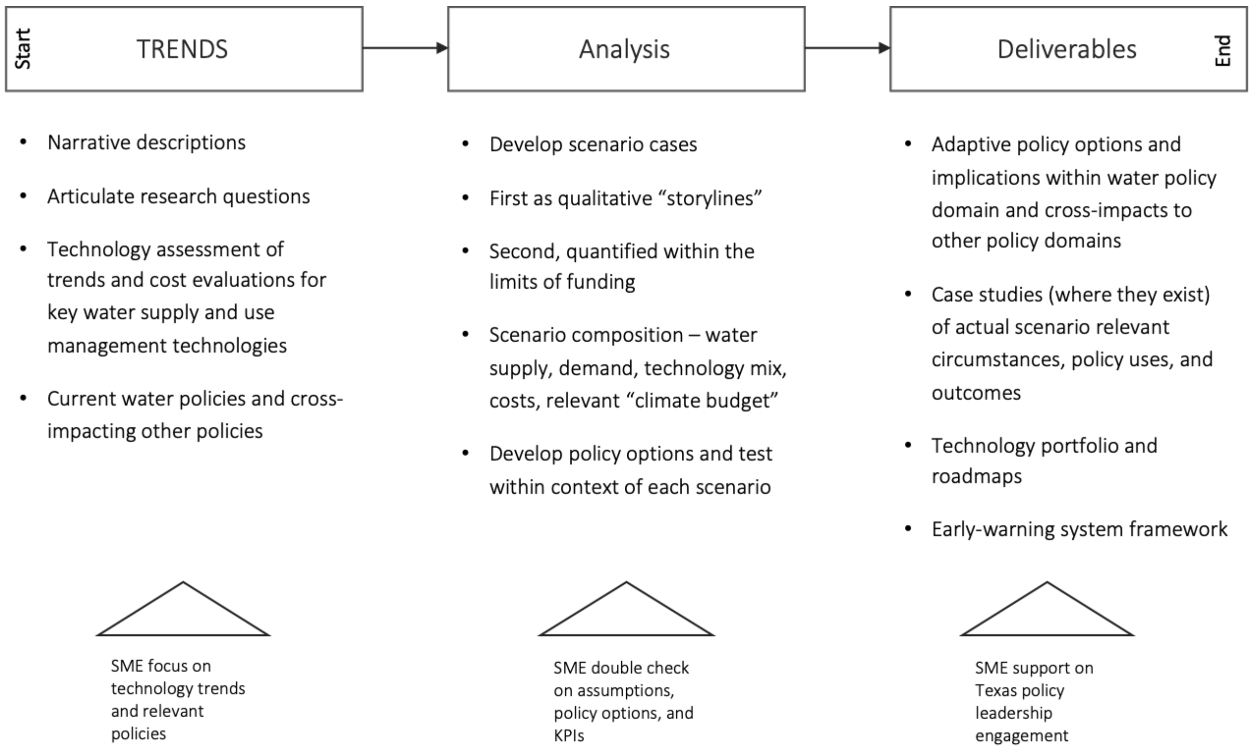

Figure 2: *Illustrative Scenario Planning Workflows*

Scenarios can also be used as overlays to existing planning methods - quantitative modeling of water supply systems provide robust tools for assessing capital expenditures and operating costs profiles that go with both short-term and long-term service reliability. Qualitative inputs using scenario techniques can be used to enrich quantitative modeling. Also, qualitative inputs can assist decision-makers in grasping implications of decision-choices necessary for ensuring reliable water supplies. More tools, rather than holding as-is, arguably serve decision-maker and managerial responsibilities for high quality reliable water service throughout the US.

4.4 Water analysis outputs to be used in scenario water planning

The following outputs of water systems analysis are keys to developing informed scenarios.

1. Final water use intensity
2. Carbon intensity and budget (water temperature change as indicator)

3. Evaporation volumes and patterns
4. Water pricing now and forecasted
5. Investment requirements
6. Water trading — imports and exports
7. Water access
8. Water use of the energy sector and impacts
9. Water quality

4.5 The organizing questions for distinctive, contrasting scenario development and use

The purpose of scenarios is to provide decision-makers with contrasting perspectives on possible outcomes of decisions made under different social, environmental, and economic circumstances. The aim is to identify the worst case possible as one bookend, and the best case possible at the other extreme. Mid-range scenarios should be designed to reflect variances from the existing present-day state.

Still, there needs to be a core organizing question to frame diverging scenarios. For example, the question might be how can water supply and use be sustainable in an age of change, with associated increasing uncertainty? Increasing uncertainty stems from climate changes that are possibly altering underlying sourcing and delivery capacity.

Scenarios that are designed and developed using the above as the organizing principle should address these questions:

1. What is the composition of future sustainable water systems?
2. How extensive must be future reservoir capacity?
3. What new infrastructure is needed to ensure long-term robust water supplies? For example, long distance aqueducts, massive investments in comprehensive recycling, such as the Hyperion project, or a long-term investment program with desalination as its foundation.
4. Can water efficiency policies function as enablers of cross-impacting policies addressing energy-water and energy-water-food interactions?
5. What are the investment requirements under each scenario for attaining a sustainable surplus water supply for a 100-year time-horizon?
6. Are there quantum transformative technologies just over the horizon that could fundamentally alter the way that water is sourced and delivered?

4.6 Inclusion of critical infrastructure planning

There is one outlier that should be considered before proceeding to explore whether and how broadened scenario planning can most effectively inform established water planning process workflows. Critical infrastructures are intersecting and interacting in ways that influence how each is managed. The infrastructures of particular concern for water planning include energy, transportation, and land use (with attention to agriculture).

These deep longstanding critical infrastructures (CIs) have distinct vertical decision, execution, and operations processes and practices. Yet each CI addresses key risk factors from other infrastructures only from its own lens. For example, water systems must have backup power supplies to hedge against electric power outages. But new correlations are emerging that merit more integration across CIs. For example, some locations in the world (e.g., local areas in South Africa, India, and Australia) must take difficult decisions as to how water supplies are used in power production, agriculture, or services to end-use consumers because the supply no longer is sufficient to cover all needs.

The next section explores cross-impacting critical infrastructure correlations with this question in mind: is it time to create a horizontal overlay on existing CI verticals?[76] If so, how might that occur?

[76] There is a general view that CI cross-impacts are accounted for within individual CI plans, which obviates the need for more integrated multi-factor CI plans. In Section 5, research shows that there is (a) less integration than presumed and (b) CI cross-impacts are increasing in complexity on the heels of climate change and other environmental impacts.

5. Critical Infrastructure and Water Planning in the 21st Century

This section examines the cross-impacts affecting critical infrastructures (CI). It presents the implications for water planning in a CI context. It articulates a framework for integrating enhanced water planning and CI planning, which could be applied at the city and state levels.

5.1 Critical infrastructure planning

Critical infrastructure (CI) has been a longstanding US concern over economic, social, and political stability impacts, as well as for matters of national security. In recent years, spates of extreme weather worldwide and related consequences (drought, wildfires, and sea level rise) have increased awareness of CI cross-impacts. Structural interdependencies and process cascade-effects are more prevalent in CI disaster planning. Wildfires in Australia and California, destructive hurricanes in the Caribbean, and the dramatic loss of ice sheets at both poles and Greenland raise awareness that CI planning must address short-term and long-term risks. Finally, these new seemingly more frequent natural events with multiple CI consequences intensify recognition that individual CIs, such as water or energy, should be addressing CI interdependencies when planning for ongoing operations and long-term sustainable service integrity.

For example, the comfort, mobility, and economic well-being of people in the US depends on reliable and affordable electric power services and sustainable water supplies. It is increasingly important. As such, it is essential to ensure continuous CI readiness. This is achieved, in part, by focusing CI sector plans on sustainability and resilience practices and processes over the mid-to-long-term. The effects of electric power and water expansion plans, water and power demand growth, disruptive impacts of climate change, and extreme events should be incorporated into Federal, state, and local power and water plans. A particular focus on costs and improved definitions of benefits are needed as part of these shifts. However, it is in the cross impacts and interdependencies of CIs especially for power and water where deeper analysis is needed to inform both sector-specific plans and CI interdependencies.

Robust quantitative planning models for both power and water can be upgraded to include CI cross impacts and interdependencies. The maturation of robust CI interdependency analysis integrated into existing power and water models, for instance, is in-flight; not evenly distributed or equally sophisticated throughout the US. An important tool to aid the maturation of CI planning elements for all CI sector plans is the contribution that scenario design, development, and use can make. Scenarios are a qualitative tool that can help bring interdependencies in essential service risks into the foreground of planning without interrupting or disrupting established operations and capital planning for power and water services.[77]

5.1.1 CI risk management and planning challenges must address ambiguous core definitions

The first step in considering CI elements in water planning is to "level set" on definitions and scoping. Each critical infrastructure sector uses many of the same terms but with distinctive CI sector specific meanings. For instance, electric power system reliability means maintaining a specific level of uptime for service delivery, e.g., 99% of the time, net of forced outages. Reliability for water systems means the

[77] James R. Thompson, Damon Frezza, Burhan Necioglu, Michael L. Cohen, Kenneth Hoffman, Kristine Rosfjord, "Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure," International Journal of Critical Infrastructure Protection, 24 (2019) 144-165.

ability to function in relation to the failure of one or several components. Similarly, it can be viewed as the ability of the system to provide a service at an acceptable level, despite failures and complex operating conditions. Of course, both water and power must ensure that all components work along the supply chain, but the meaning of component in water differs from its meaning in power. The difference in meaning is found in how each CI delivers its essential service based on equipment required — in the case of water, pumps matter; but in the case of electricity, fans and heat transfer equipment matter more.

Critical infrastructure is vertical in this sense: energy, information and communications, water, and other structures are end-to-end supply chains or "techno-industrial ecosystems" whose continuous operations are critical to economic and national security.

Also, CIs are "horizontally coupled" through structural and process links. Links are interdependencies, or partial correlations, between two or more critical infrastructures, where either endogenous or exogenous events impact other CIs. In some cases, links are limited to cross-impacts between two structures, e.g., energy and water. In other cases, events in one structure cause cascading impacts in several CIs. The global pandemic of 2020 is a perfect storm of multi-CI impacts.

Interacting event-driven complications are the focus on which CI planning takes place. It is not singular events per se that are of greatest concern. It is multiple events of the same type repeatedly happening. It is the interdependencies between two or more CIs that are main concerns for CI planning. The underlying question is how redundant and resilient are CI platforms when handling repeated cross impacting events.

5.1.2 Interdependency is a predominant focus

Interdependency means there is a dependency link or connection between two or more infrastructure systems. Generally, there are four types of CI interdependency — physical, cyber, geographic and policy.

- *Physical interdependency* is related to material flows between infrastructure systems. For example; a gas or coal-fired power plant relies on transportation systems to ship raw materials while the transportation system depends on a continuous supply of electricity.

- *Cyber interdependency* is concerned with dependencies on information flowing through cyber channels, which are critical for economic and social commerce as well as broad and deep national security assurance.

- *Geographic interdependency* involves physical proximity of CIs, which can trigger multiple events simultaneously or as a cascade effect. For example, electricity supplies to gasoline stations; when power goes out, gas dispensing goes down, and transportation risks rise leading to impacts on food supply chains.

- *Policy interdependency* includes decisions and directives that disrupt CI equilibrium, e.g., a policy that reduces the frequency of water quality monitoring at a water treatment plant can increase the probability of contaminated drinking water.[78]

CI increasingly is subject to risks associated with physical threats and natural disasters; but more important is the rising exposure and impact risks to cyber systems. These new risks stem from growing integration of information and communications technologies with critical infrastructure operations. The increasingly ubiquitous importance of cyber systems comes with new sources and types of threats — adversaries focused on exploiting potential cyber vulnerabilities may attack directly or navigate CI interdependencies to drive disruption. The reliance on information and communications technologies have increased the potential vulnerabilities to physical and cyber threats; the potential consequences of compromised systems are still being discovered through analytical modeling and facing actual cases.[79]

Finally, vulnerabilities also may exist as a result of a retiring work force or lack of skilled labor. Skilled operators are necessary for infrastructure maintenance and, therefore, security and resilience. These various factors can shape the risk environment, creating an often unprecedented backdrop against which ad hoc decisions are made for critical infrastructure security and resilience. Ad hoc decisions may be necessary, but for large-scale institutions, ad hoc decisions cannot be adopted as standard operating procedure. It is important for leaders to drive converting necessary ad hoc action into essential institutional practices and processes.

5.1.3 Standardize terms to ensure smooth management of disruptive CI events

Critical infrastructure protection and assurance is complex. It manifests itself in several ways:[80]

- *Lack of a shared understanding of terminology* from CI to CI; e.g., quality assurance (QA) for cyber is focused on barriers to cyber-attacks while QA for energy is focused on reliability of service delivery; a shared process definition of QA for CI is missing.
- *Precision of definitions enables rigorous meaning to be conveyed concisely,* which is important in circumstances where one CI leads to other CI impacts — in other words, all interdependent CIs should be able to answer in the same way a question such as “have you checked QA as the root cause?”
- *Confusion from the policy environment* — often, the diversity of government and public perceptions cloud the meaning of actions taken to design, evolve, assure, and protect CIs, which has the effect of perpetuating existing confusion or introducing new forms of confusion regarding planning processes and deliverables as well as implementation of actionable directions.
- *Private sector owners of CIs exhibit defensive postures* regarding government motives and capabilities even though the priority is ensuring national security.

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[78] Jui-Sheng Chou, Citra S. Ongkowijoyo, “Hybrid decision-making method for assessing interdependency and priority of critical infrastructure,” International Journal of Disaster and Risk Reduction, 39 (2019).

[79] US Department of Homeland Security, NP 2013: Partnering for Critical Infrastructure Security and Resilience. p. 7 - 8. Available at: https://www.cisa.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf

[80] DOD, Ibid.

The DOD's early positioning on CI planning and management was extended when post-9/11 Department of Homeland Security (DHS) CI planning emerged. DHS focused on the interconnectedness and interdependency within the nation's critical infrastructures. Its planning focused on each individual CI sector addressing interdependency with other sectors within specific sector plans.

For example, the Department of Energy (DOE) as the Energy Sector-Specific Agency, focused on a comprehensive understanding of interdependencies. The focus was adumbrated to mitigating only energy sector potential vulnerabilities. Similarly, the Environmental Protection Agency (EPA), as the Water Sector-Specific Agency, addressed its links with the Energy Sector as the primary interdependency.[81] Secondary effects, risk augmentation, or residual problems were not then nor to this day have they been considered with equal attention.

DHS recognized perceived threats to national security as not only "critical," but more "interdependent" than previously understood by CI leaders and managers. Extending the example of system interdependencies in the "energy/water nexus" — modern electric power plants depend on water supply for cooling overheating generators, and water supply plants depend on electrical energy to pump huge volumes of water around a city, where any disruption to one system spills over into others. Such dynamics are referenced as "ecosociotechnical," i.e., that ecological, social and technological systems are inherently connected (well past primary factors and into secondary and deeper impacts) whether recognized or overlooked. [82]

5.1.4 Cascade effects and collateral impacts from CI interdependencies

The term "ecosociotechnical" emanates from recognizing two barriers to achieving shared multi-CI standards. The science and engineering side of CI is generally isolated from social and broad ecological perspectives held by institutional managers and various stakeholders. On one hand, this isolation can limit the variables being analyzed. In turn, this can limit the perception of circumstances requiring broader consideration, e.g., QA on water quality may focus on decontamination processes, which could be reduced or eliminated if ecological effects on upstream reservoirs were recognized, understood, and addressed.

On the other hand, enterprises intentionally act to lower costs by externalizing wastes or residuals left after manufacturing, or other processing, e.g., how polycarbonate plastics are recycled can increase or decrease local ecological impacts and/or extend into regional systems. If an enterprise external diseconomy impacts other systems, especially CIs, but it is not recognized or is ignored, consequences may become a visible burden to others possibly separated by two or three degrees.

No single CI sector can have full knowledge of how its operations may impact other CIs. However, for significant risk pathways, such as how enterprise externalities are handled, can be understood and mitigated, both within the source-CI sector and amongst other CI sectors.[83]

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[81] James R. Thompson, Damon Frezza, Burhan Necioglu, Michael L. Cohen, Kenneth Hoffman, Kristine Rosfjord, "Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure," International Journal of Critical Infrastructure Protection, 24 (2019) 144-165

[82] Moore, et.al., Ibid.

[83] Moore, et.al., Ibid.

In every system — ecological or "human ecological" — weak links define the limits to its resilience and adaptability. In CI systems, weak links and vulnerable interconnections can yield failures in one system which trip failures in other systems. For example, a failure in a telecom infrastructure, e.g., network base stations, may bleed into electricity distribution network operations as digital control assets are disrupted. This in turn can impact the other infrastructures, e.g., water and transportation, leading to a broader and/or cascading failure in materials flows, information flows, or collateral damage to geographically proximate systems and/or operations.[84].

5.2 CI interdependencies and implications for water planning

5.2.1 Operations, systems, and institutional congruence factors affecting CI interdependencies

CI interdependencies in water planning, particularly at the intersection of water and energy, merit inclusion in contemporary water planning. The complexities and ambiguities of CI cross impacts mean qualitative scenario processes can be used to enhance CI sectoral plans.

CI interdependencies are operational — loss of power can shut down communications, transportation, and other energy supply systems. Operational cross impacts are institutional challenges as much, if not more, than core systems challenges. Institutional behavior influences interactions amongst CIs that determine the effectiveness of resilience management.

The underlying critical success factor to maximizing effective coordination among actors across complex systems is the extent to which similar, agreed upon, or harmonized terms and conditions of event management exist. This alignment sits under the rubric, "Institutional congruence." It is a critical success factor that tends to be underemphasized in CI interdependency planning.

For example, a study of how organizations coordinated during Hurricane Harvey in Harris County showed that although non-structural solutions were supported by most of the cross impacted organizations involved in hazard mitigation, existing plans that guided hazard mitigation did not specifically focus on cross impacting CI interdependencies. The root cause of incongruence amongst institutions was the friction inherent in responsibility sharing among government functions at different levels of hazard mitigation efforts. Different organizations across CI sectors had varying perceptions regarding suitable approaches for flood risk mitigation that contribute to the vulnerability of physical infrastructures.[85]

5.2.2 Questions for CI sectoral plans to enhance CI interdependency links

The following are generalized (indicative) questions that can be used to initiate the crafting of scenarios and/or serve to ensure stronger links between various CI sectoral plans.

1. What are the most likely cross impacting events that could disrupt water service operations for short-term or long-term durations?

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[84] Seppanen, et.al., Ibid.

[85] Hamed Farahmand, Shangjia Dong, Ali Mostafavi, Philip R. Berke, Sierra C. Woodruff, Bryce Hannibal, Arnold Vedlitz, "Institutional congruence for resilience management in interdependent infrastructure systems," International Journal of Disaster Reduction, 46 (2020).

2. What are the extreme or unprecedented possibilities that could similarly disrupt water service operations?

3. What are the critical institutional congruences to ensure efficiently and effectively workable processes and decision-making when managing a hazard or other disruptive event? Are they different for cross impacted CIs than for intra-sectoral CI plans? If so how?

4. What level of contingencies should be included in plans? Examples: capital contingencies, asset inventories, supplementary support staff and field operations, communications infrastructure, fuel supplies and surpluses. These items should be derived as part of CI interdependency planning workshops, to be discussed below.

CI sectoral interdependency questions should be developed to fit specific organizations and locations, or state level planning efforts within and between CI sectors.

5.3 Nested critical water infrastructure planning

Nearly all other US critical infrastructure sectors depend on power and water to produce goods and services; drawing upon natural water resources to enable the provision of lifeline services. When natural water resources become scarce due to drought, disasters, or mismanagement, electric power, water and wastewater systems may compete for water resources. In a worst-case scenario, the scarcity of natural water resources could result in electric power and water shortages that adversely affect the health and economic wellbeing of a region.

The linkages between diverse CIs, therefore, are not equal in significance or priority. They are nested because power and water can determine the capacity of other CIs to function under extremely disrupted circumstances.[86] However, this does not mean they are "uncorrelated." Analytical models show that over the longer term a disturbed infrastructure with only a reduced performance level draws all other CIs to the same reduced performance level. Further, even after full restoration of CIs, their near-term performance cannot return to full operations without external support, principally through funding but also through systems integration congruence[87].

An example is relevant. Power systems are known as smart grids where digital information is transmitted in real-time from end-to-end of a power grid. These smart systems are increasingly necessary to deal with instabilities in power grids coming from variable energy sources, like wind, as well as variable end-uses, mostly electronic and computational platforms. Smart systems have intrinsic vulnerabilities, i.e., a smarter power grid is more reliant on an information-communications technology (ICT) backbone. Accordingly, security for such systems depends on a set of metrics and standards unfamiliar to institutional conventional electric power delivery systems. The sustainability of a power

[86] A caveat to this general point is that increasingly, other CI sectors are developing resilience plans and assets, which enable autonomous or near-autonomous operation during an electric power outage of sustained duration. Insofar as water infrastructure is provisions for continuous operation during a power outage, its risks to economy and society are reduced (assuming core water supplies are not diminished to a point where zero-sum tradeoffs between energy and other CI have to be made.

[87] Peter Klein and Fabian Klein, "Dynamics of interdependent critical infrastructures – A mathematical model with unexpected results," International Journal of Critical Infrastructure Protection, 24 (2019) 69-77.

system will depend on the secure and reliable operation of the new smart system;[88] hence, dependence on CI sectors interdependently impacted by disruptive events.

The outcome of events and event restoration noted above reveal a nested ambiguity to CI interdependent planning. The ambiguity is a function of institutional incongruity and the inherent uncertainty of unprecedented cross impactful events. Until there is a richer pallet of cases in this important CI interdependency planning space, SMEs tasked with imagining reasonable possibilities as well as extreme events, which could lead to more or less catastrophic infrastructure consequences, are a low cost-high content pathway to increasing the robustness of water and power planning in particular.

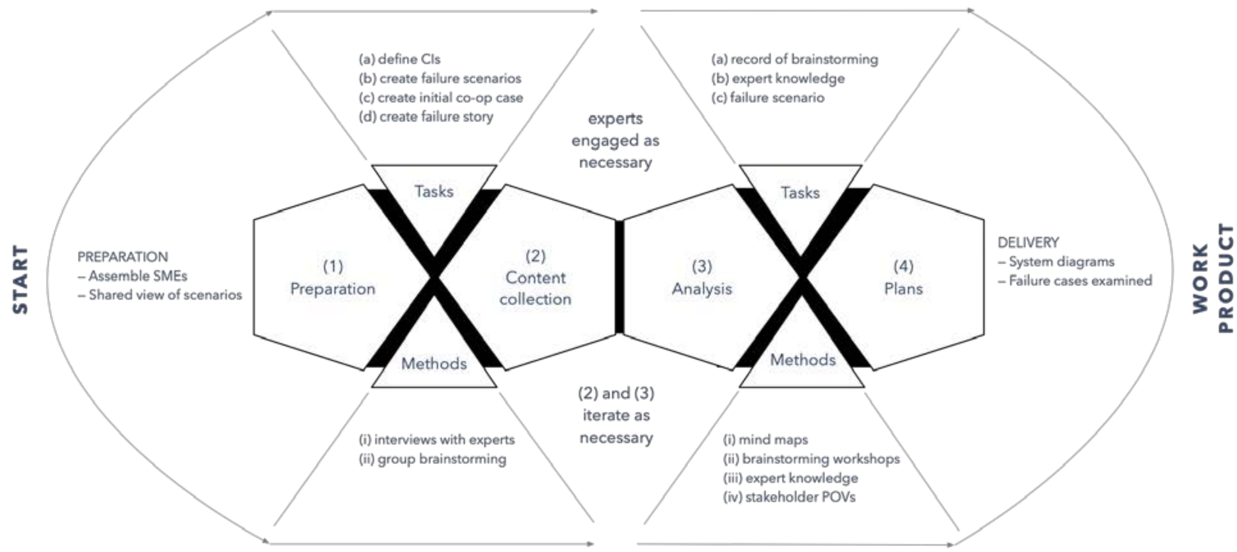
A scenario approach is a significant value-add to contemporary planning within CI sectors because CI exposures and potential impacts are distinctive at local and regional levels. National level CI planning and management, by contrast, can be focused on sources of system failures, the hardening of system structures and processes, and the mitigation of CI impactful events, such as extreme hurricanes, or pandemic management.

Using scenario planning practices provides for enhancements to core water planning models and practices, which can be thought of as nested processes. That is, CI considerations treated as part of qualitative scenario development to inform core water planning tools do not burden core planning activities with costly new quantitative modeling requirements.

Over time, "nested CI planning" can be included in core water planning efforts, CI cross impacts can be programmed into quantitative models to further enhance water planning effectiveness. Finally, these steps serve decision-makers by providing event possibilities and related failures for their consideration.

Figure 3 below provides an illustrative CI scenario planning map that can be tailored to specific water utilities or other entities, such as state level water oversight and management departments.

[88] Baraa Mohandes, Reem Al Hammadi, Wasiu Sanusi, Toufic Mezher, Sameh El Khatib, "Advancing cyber–physical sustainability through integrated analysis of smart power systems: A case study on electric vehicles," International Journal of Critical Infrastructure Protection, 23 (2018) 33-48.



Author's rendering inspired by:
Hannes Seppänen, Pekka Luokkala, Zhe Zhang, Paulus Torkki, Kirsi Virrantaus, "Critical infrastructure vulnerability—A method for identifying the infrastructure service failure interdependencies," International Journal of Critical Infrastructure Protection, 22 (2018) 25-38.

Figure 3: *Critical Infrastructure Interdependencies Developed into Workable Failure Cases*

CI scenario processes are visually depicted above. The workflow begins with assembling SMEs and crafting initial scenario frames. Main tasks in preparation include defining the scope and characteristics of CIs that impact water, or vice-versa. Once characteristics are mapped, failure scenarios can be developed against an initial core operations case. The preparation phase ends with creation of failure stories.

Stories need to be enriched in complexity to be meaningful. SMEs are engaged as necessary to build content. Planning staff manages analysis and iterates with SMEs as needed until a satisfactory set of stories is developed.

Once stories are sufficiently robust, engagement with SMEs occurs; planning in brainstorming focused on how CI impacts might unfold under different event profiles and induced failures is the focus. The deliverables are system diagrams mapping how events and failures cascade. Failure cases run as simulations are used to assess impacts and the mitigation of impacts.

5.4 Integrating CI sector planning into established resource planning models

5.4.1 Institutional differences as both barrier and opportunity

Core water planning focuses on operational integrity for maintaining reliable, resilient, and clean water services for end-users of all types. Meeting growing demand is a prime focus, which involves both operational and capital planning for near-term and longer-term efforts to avoid shortages. Today's water planning processes in many US states recognize mutual dependence on the same water resources for both power production and water services. However, organizational barriers, differences in planning cycles, differences in geographic jurisdiction, and limited joint planning tools, yield power and water interdependency planning that is rudimentary compared to the scope of the present and impending challenges related to both power and water (which implicitly calls for more robust joint planning).[89]

The institutional differences between power and water planning, i.e., jurisdictional misalignments at the local level, nominate state level planning processes as integrators of multiple CI sector plans. Execution of such responsibilities could occur through state level functions or a distinctly purposed entity addressing CI interdependencies and their impact on state and local level CI sector planning.

For example, the use of water for power generation involves both withdrawals and consumption. Withdrawal means water is passed through a steam condenser and returned to its source as heated water. Consumption means the water is used for cooling and other purposes, ultimately being discharged in waste streams or evaporated to the atmosphere.[90] When power and water critical infrastructures are treated as components of one system — and their respective components are looked at individually — a complex interdependent system is revealed as a continuously adapting collinear vital service system for communities. Circumstances can change the delivery capabilities of essential services (e.g., meeting demand volumes, or ensuring water availability). When triggered, interdependent components of CI sectors can react in different, often unexpected, ways. New forms of agent-based modeling (with both quantitative and qualitative aspects) offer tools for capturing cross impacting CI sector behaviors.[91]

5.4.2 Research on institutional convergence in the City of Austin, Texas

For example, researchers at the University of Texas in Austin are studying CI cross impacts in a microcosm around the Solutions-Driven Community Center (SDCC) in Austin. One focus of the research is on how (institutional) pragmatic experience and the division of both knowledge and labor enable or disable effective mitigation of CI cross impacts. Understanding these characteristics can enhance institutional management to mitigate organizational friction that can produce ecological, sociological, and technological (i.e., ecosociotechnical) consequences; so, the better the management the higher the quality of community life. Said as researchers say it, the research offers "a method to align frames of interpretation through collective action in Austin.[92]

The case of the city of Austin's decades long conflict over electricity rates illustrates the point.

> "On one side of the dispute, the city-owned utility (Austin Energy) has found it prudent to reduce rates and increase reliability, but only for industrial-scale consumers. In other words, small households that consume the least amount of electricity per person pay a disproportionate share per kilowatt hour. This policy has been supported by environmental groups. On the other side, low-income community groups, supported by the Roman Catholic Diocese, oppose such preference

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[89] James R. Thompson, Damon Frezza, Burhan Necioglu, Michael L. Cohen, Kenneth Hoffman, Kristine Rosfjord, "Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure," International Journal of Critical Infrastructure Protection, 24 (2019) 144-165.

[90] Thompson, et.al., Ibid.

[91] Thompson, et.al., Ibid.

92 Steven A. Moore, Marla Torrado, Nicole Joslin, "Knowledge production for interdependent critical infrastructures: Constructing context-rich relationships across ecosociotechnical boundaries," Environmental Science and Policy 99 (2019) 97-104.

> because, (1) the policy effectively increases living costs of the poor, and (2) leaves them more vulnerable than businesses to power-outages and attendant health threats. Although negotiations have been attempted, the competing interests have not worked together to imagine a solution. This case is a good example of context-poor versus context-rich interpretation in which the SDCC might engage."[93]

Moore, et.al., extends the above point to illustrate techniques that can be applied to addressing context-poor versus context-rich interpretations. City neighborhood associations along with city-owned electric and water utilities, a mix of appropriate city offices and departments, as well as university, architectural, and planning experts could work together to develop an approach to an array of possible solutions to cost impacts across various socioeconomic categories, including district heating, cooling and water sequestration.

> "It is known that, at certain densities, neighborhood-scale infrastructures are more energy- and water-efficient. It is not known, however, what kind of social organization could manage such a highly integrated technology. Through such experimentation, new frames of interpreting possibilities and knowledge would be produced."[94]

Ecosociotechnical institutional congruence studies in Austin illustrate the potential for helping address important CI interdependency challenges at the interface between CI sector plans. However, recognition is not execution, and execution cannot be activated absent state level and/or regional level policies that require enhanced water planning, which incorporates explicitly multiple CI interdependencies. Doing so then leads to the planning process challenge of how to marry deeply detailed quantitative planning models in both energy and water sectors with CI interdependency issues, which still remain more qualitative than quantitative.

The answer, as noted, is to leverage mature qualitative planning processes broadly referred to as "scenario planning" in service to both contemporary water planning and emerging needs for CI integrated planning.

5.5 Recommended steps forward

This paper calls out opportunities for enhancing water planning, which enables the state, its cities, and water planning districts to incorporate more qualitative possible risks and opportunities that bear on both near-term and longer-term planning horizons. Scenario planning practices were discussed. Illustrations for how to integrate broad-based scenarios were included. They leverage existing narrow-cast scenarios used for assessing the robustness of quantitative water plans.

One additional consideration emerged from review of city and state water plans and covering relevant academic and trade literature on water planning. Over the last two decades, critical infrastructure planning has become a more important framework. It can be applied to existing planning systems and processes or it can be leveraged to create a new interstitial level of planning that integrates diverse CI plans. This enables individual plans to be more robust in dealing with essential services events. It also enhances state level plans for how to ensure effective coordination and mutual support across CIs

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[93] Moore, et.al., Ibid.

[94] Moore, et.al., Ibid.

running up to, during, and closing out severely disruptive events, such as droughts, flooding, or other natural or human induced attacks.

ISE recommends taking the following steps to evaluate and then determine if contemporary planning systems and processes across CIs are adequate or warrant enhancements. A sequence for doing so includes these steps:

1. Conduct a statewide review of existing critical infrastructure plans and identify the extent of integration for dealing with cross impacting interdependencies.

2. Based on findings in (1) develop a prototypical integrated CI planning process that leverages existing planning and minimizes added costs while maximizing added benefits in each of the main CI sectors.

3. Following the work in (2), conduct a pilot program that adds scenario planning to contemporary infrastructure planning and uses scenario planning techniques to create planning tools that help to integrate CI sector plans into an overall, comprehensive CI plan for the state and its cities.

Perhaps the most significant finding of this research is the scope of essential service interdependencies in the energy-water-food nexus that seems to stand alone when at the heart of each resides difficult allocation tradeoffs all decision-makers would prefer to avoid having to make.

ISE recommends that this constellation of planning domains and how they overlap become the new framework for essential service and critical infrastructure planning at the state level. Extending contemporary CI planning relevance can ensure safe, reliable, and affordable essential services for the 21st Century.

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